TELECOMMUNICATIONS, COMPUTER ENGINEERING, AND PHOTONICS INSTITUTE

Sant'Anna School of Advanced Studies – Pisa

ICT COISP
Information and Communication Technologies for Complex Industrial Systems and Processes

eliSo European University

PLATEA

Research Fund for Coal & Steel

CONTROL IN STEEL

Cyber-Physical Systems for Production Simulation and Optimization within Complex Industrial Systems

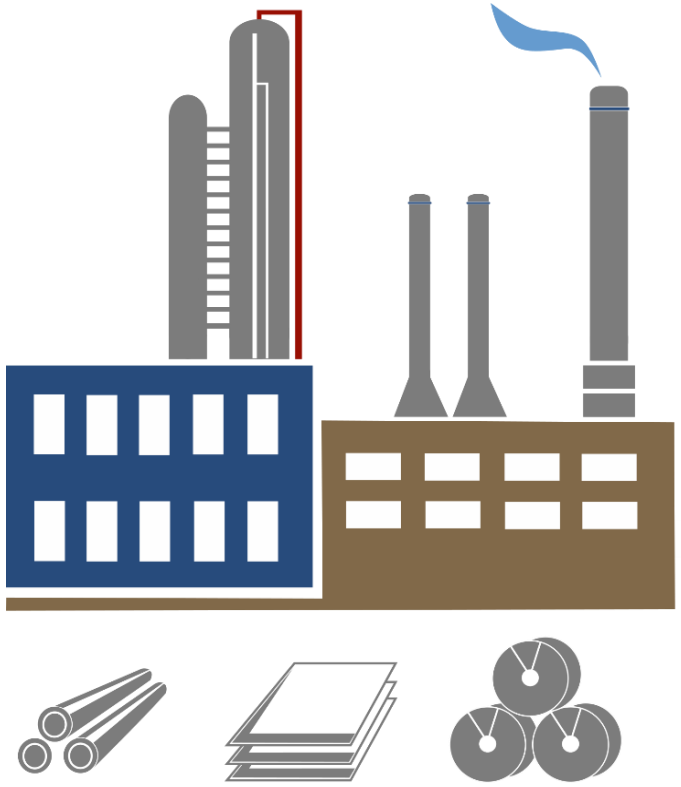
Vincenzo Iannino

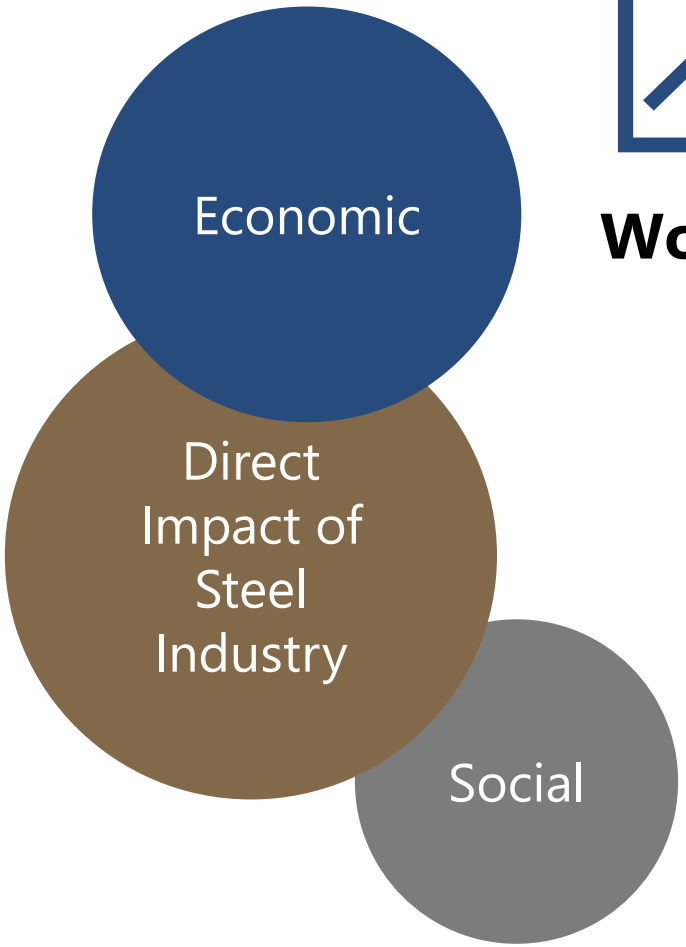
Scuola Superiore Sant'Anna

International Seminar: Digitalization as Key Driver in the Steel Industry
Cases from some RFCS funded projects

Steel Manufacturing Industries

Facts at Glance





2.5T

Worth of products

500B

Value for the economy

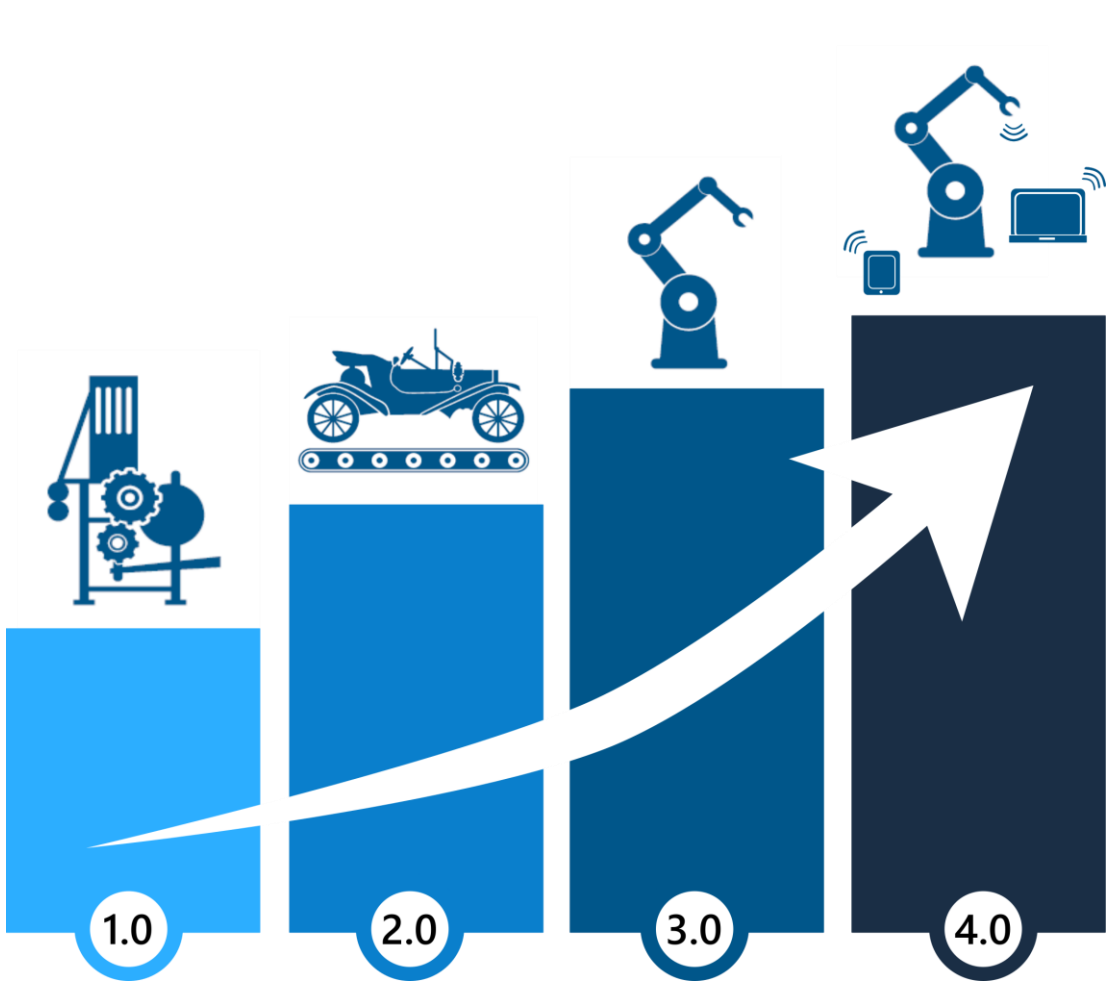
6.1M

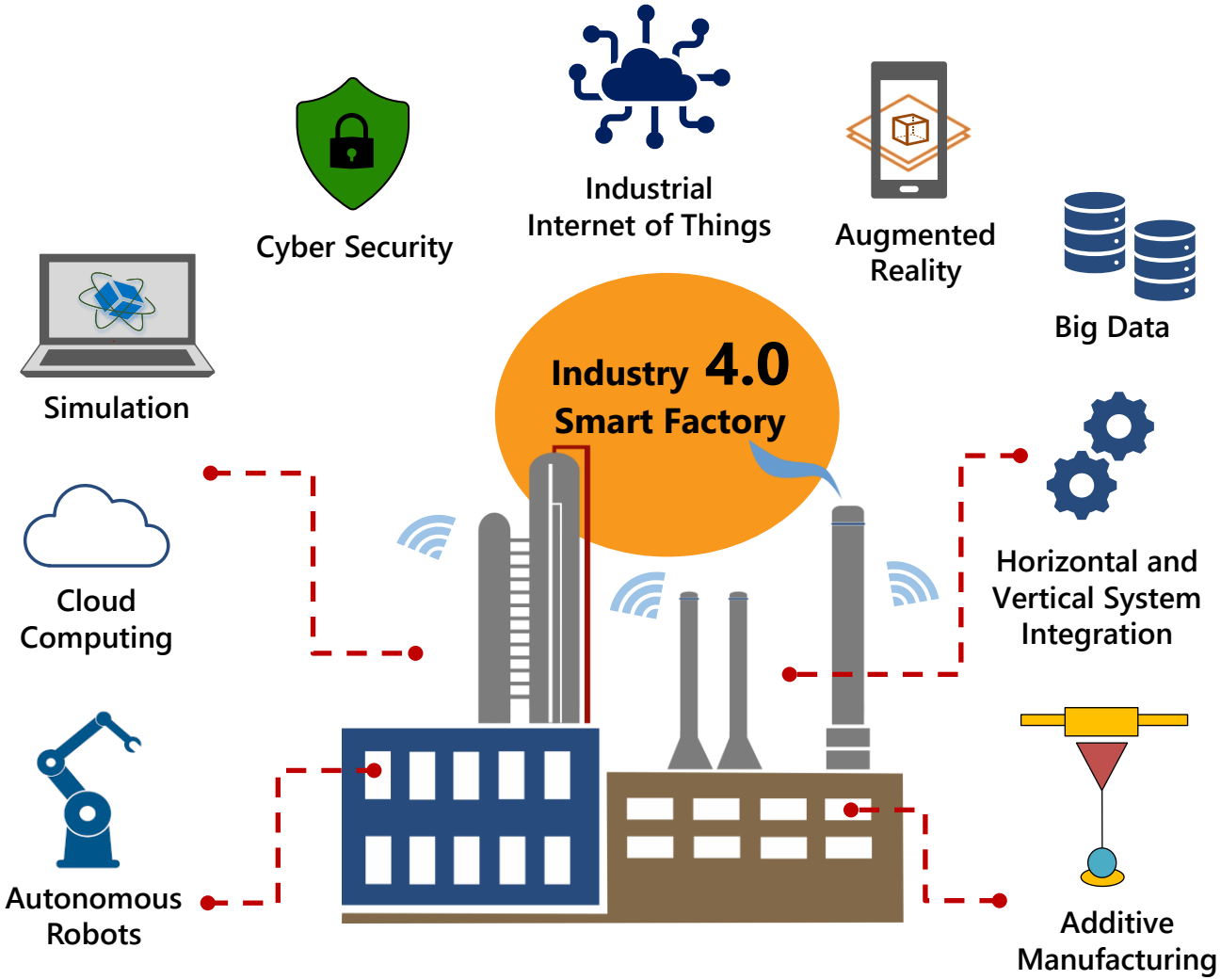
Employed people

*Source: Oxford Economics (estimates based on 2017 data)

Steel Manufacturing Industries

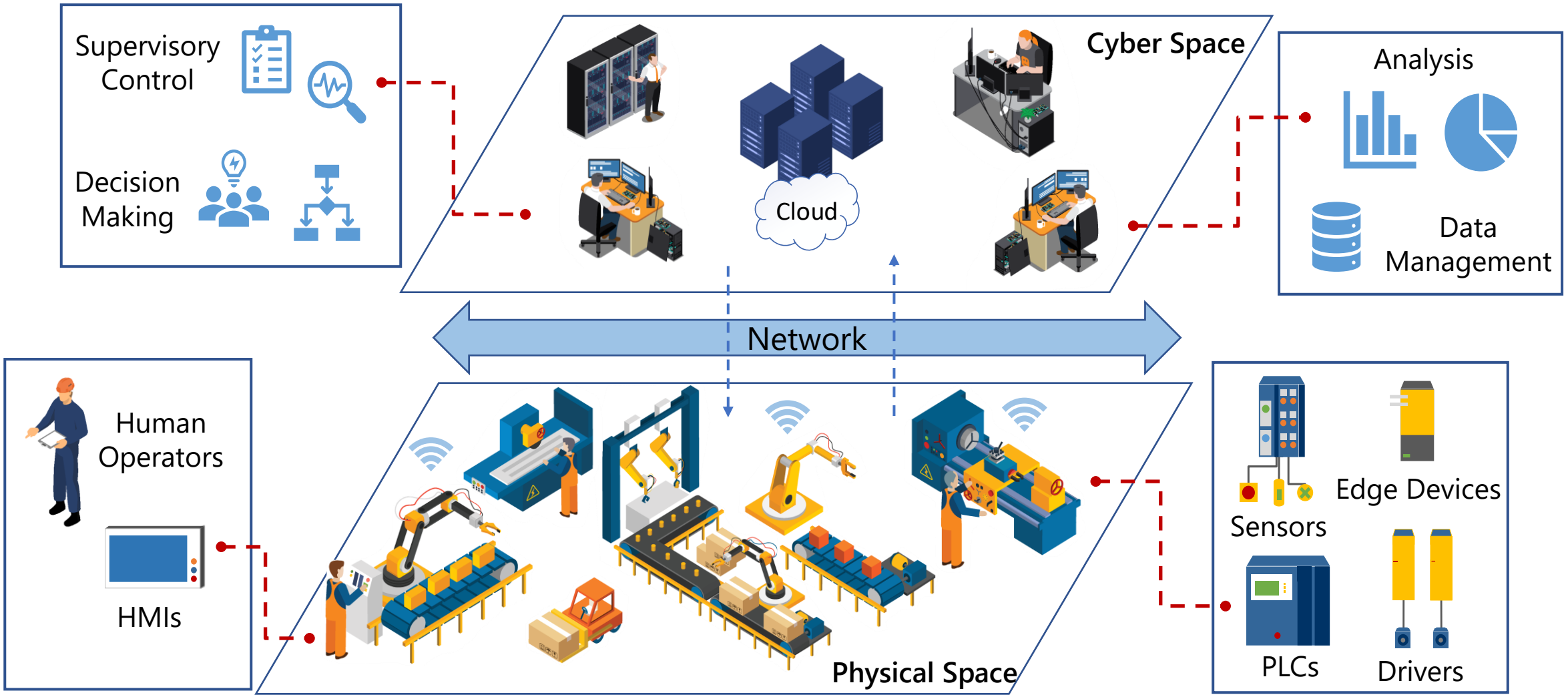
The New Era of Industry 4.0





Steel Manufacturing Industries

Cyber-Physical Production Systems (CPPS)



Steel Manufacturing Industries

CPPS Barriers

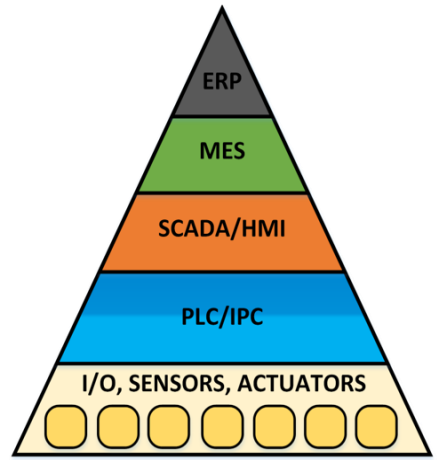
Research studies show **companies hesitate to make use of Industry 4.0 applications** regardless of the many chances these technologies might hold[1]

Designing complex **CPS** is a demanding task and **requires integration of different technical disciplines** and different application domains

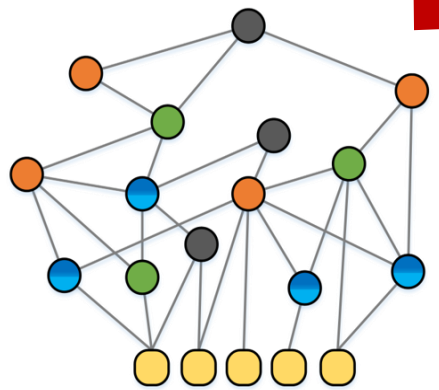
Moving from **traditional control** structure towards a **CPS-based one** requires **new hardware** and **software technologies, embedded sensors/actuators,** and **network integration**

Existing **industrial standards present some limitations for** a wider acceptance of CPS[2]

CPS reference architecture models provide a technology-neutral starting point, they **lack a recommendation for how to realize such an architecture**. Moreover, the **support** needed **for legacy systems is** only **partly considered**[3]



ISA 95 Automation Structure

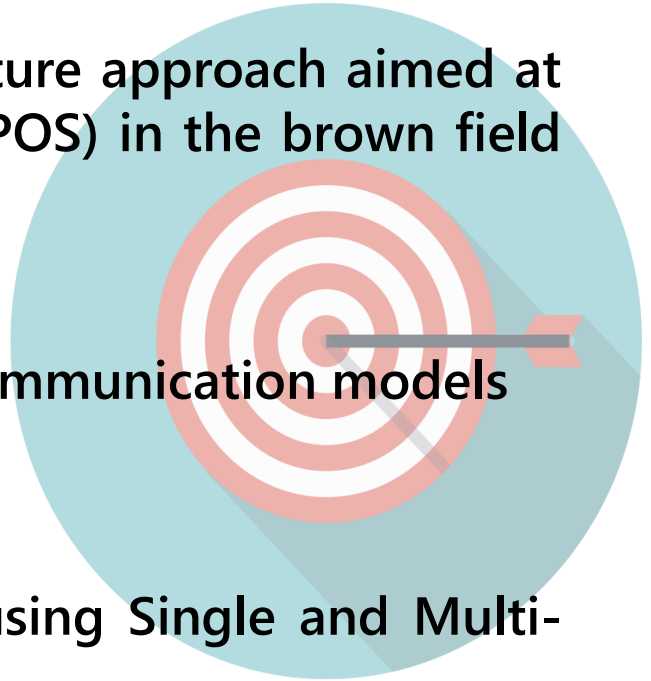


CPS-Based Automation Structure

[1] R. Glass et al., "Identifying the barriers to Industrie 4.0," *Procedia CIRP*, vol. 72, pp. 985–988, 2018
[2] P. Leitão et al. "Standardization in Cyber-Physical Systems: The ARUM Case", in Proc. of IEEE Int. Conf. Ind. Technol., pp. 2988-2993, 2015
[3] E. Trunzer et al., "System architectures for Industrie 4.0 applications: Derivation of a generic architecture proposal," *Prod. Eng.*, vol. 13, pp. 247–257, 2019

Research Objectives

Promote the design of CPPS with a concrete modular architecture approach aimed at enabling Cyber-Physical Production Optimisation Systems (CPPOS) in the brown field areas of steel industries



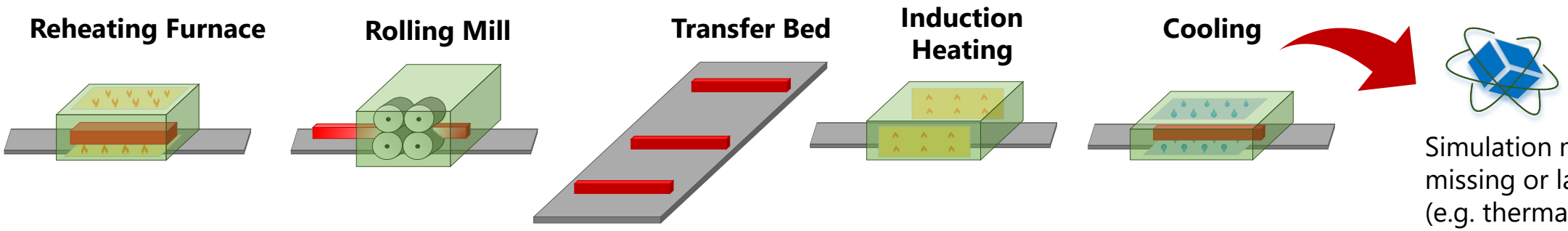
Combine appropriate process models as well as logistics and communication models

Implement a model-based through-process optimization by using Single and Multi-Objective Optimization techniques

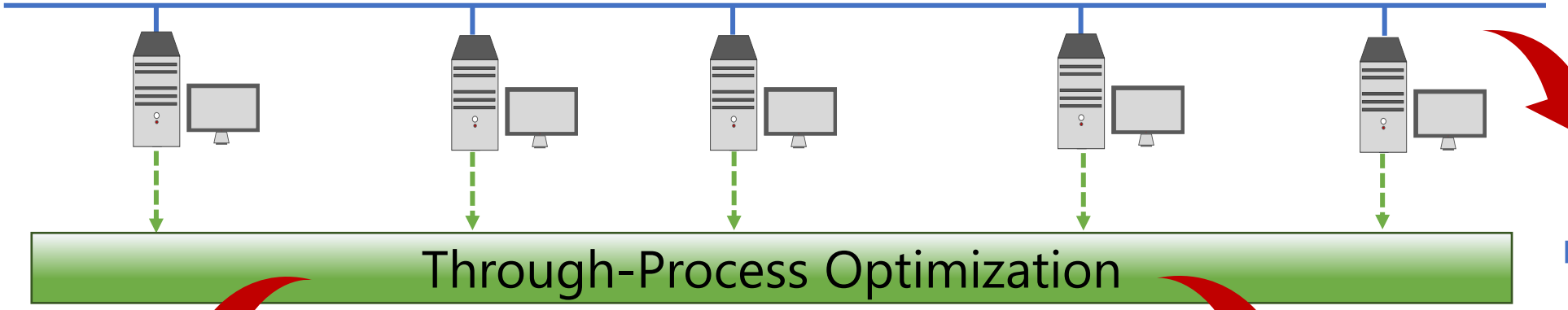
Provide an industrial agent-based solution for the realization of CPS modules considering legacy automation systems

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

The Need of Through-Process Optimization and CPPS



Simulation models are still missing or lack in accuracy (e.g. thermal evolution)



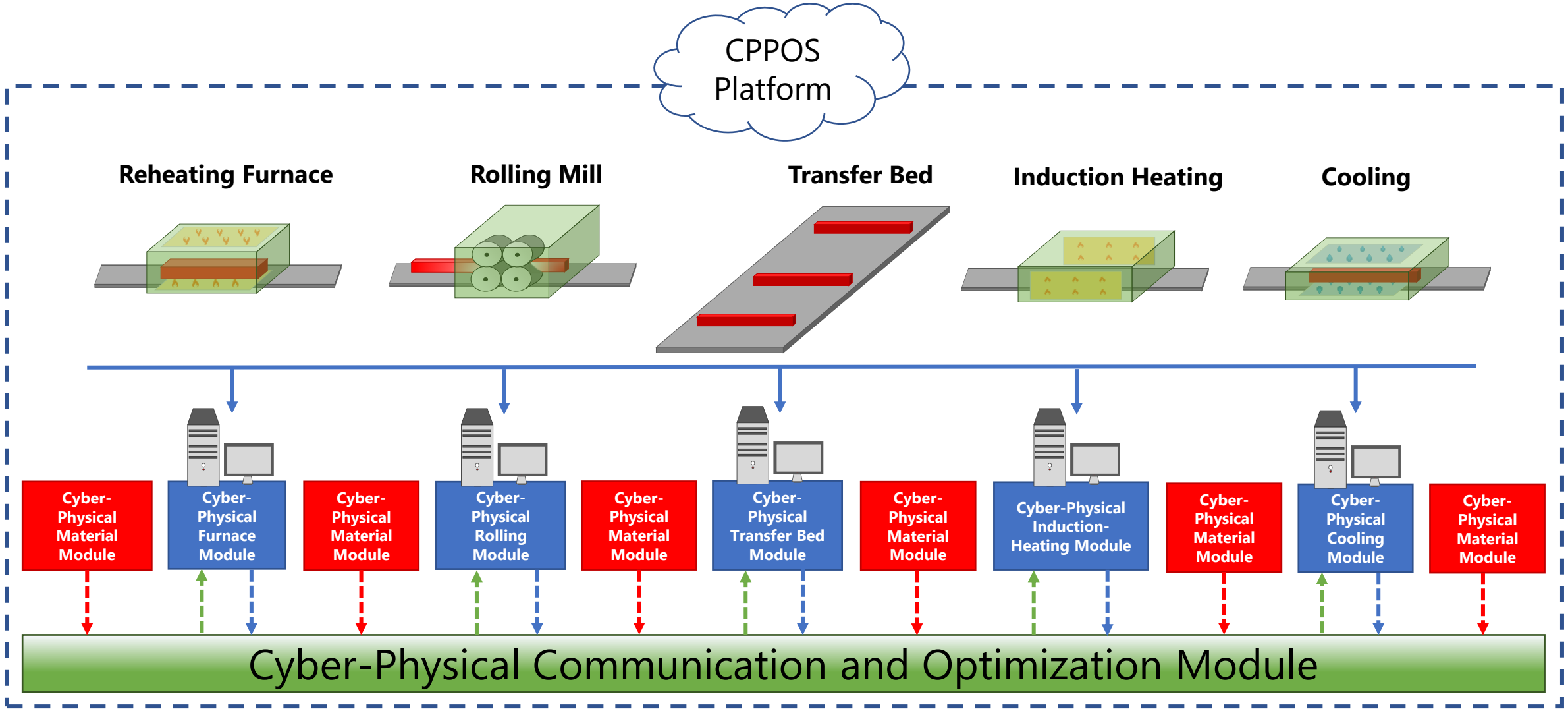
Missing of standardized interfaces between the aggregates

The traditional optimization focused only on individual process separately

No overall through-process optimization is possible due to missing inter-process communication

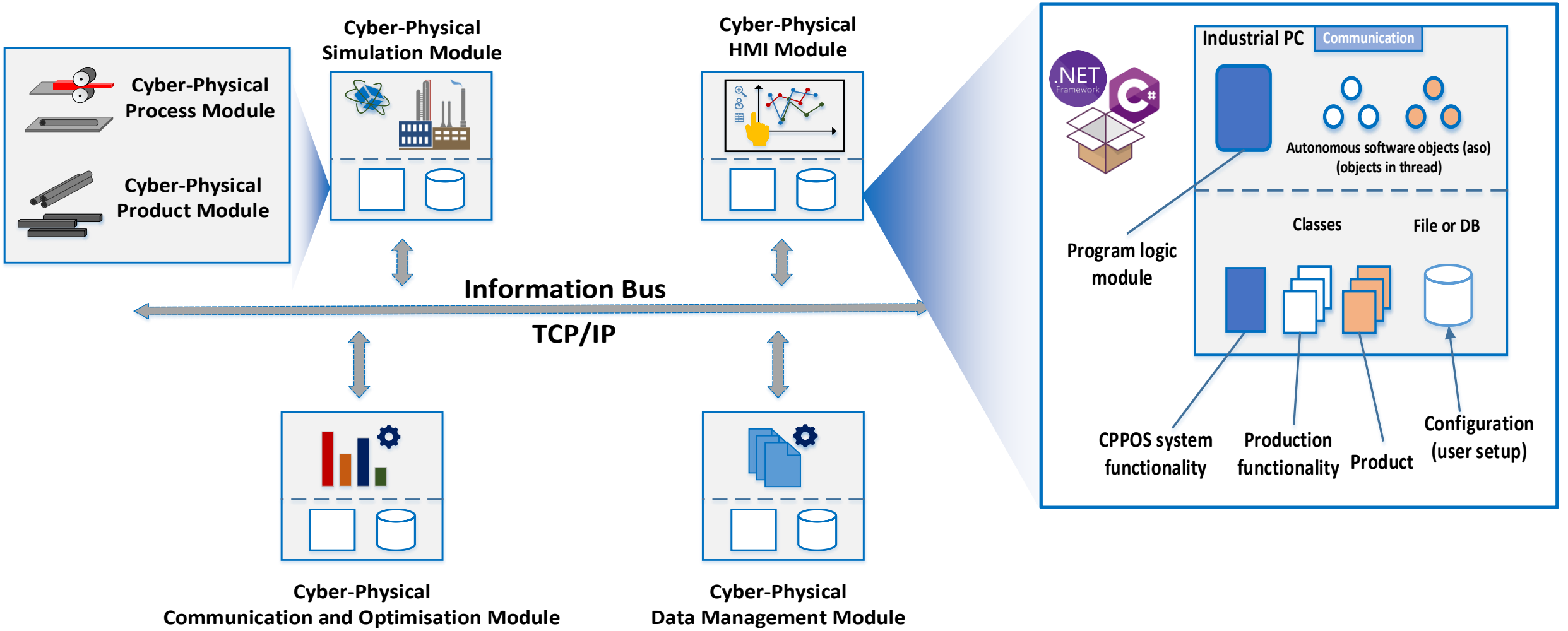
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

CPPOS Platform Concept



Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Application-Oriented CPPOS Architecture Design



*V. Iannino, V. Colla, J. Denker and M. Göttsche, "A CPS-based simulation platform for long production factories," *Metals*, vol. 9, no. 10, pp. 1-20, 2019

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

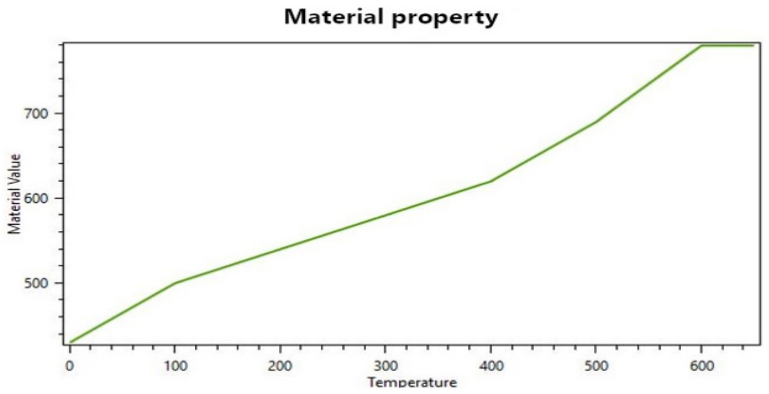
Application-Oriented CPPOS Architecture Design: Product and Process Modules

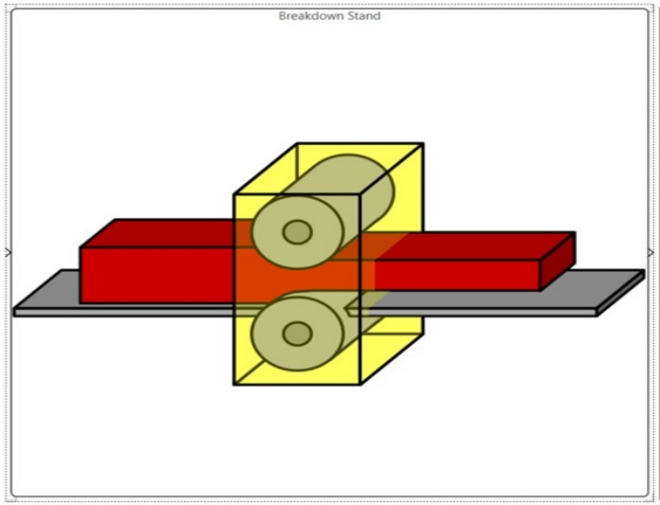
Name
Material 1

Property
SpecifiedHeatCapacity

Unit
J/(Kg*K)

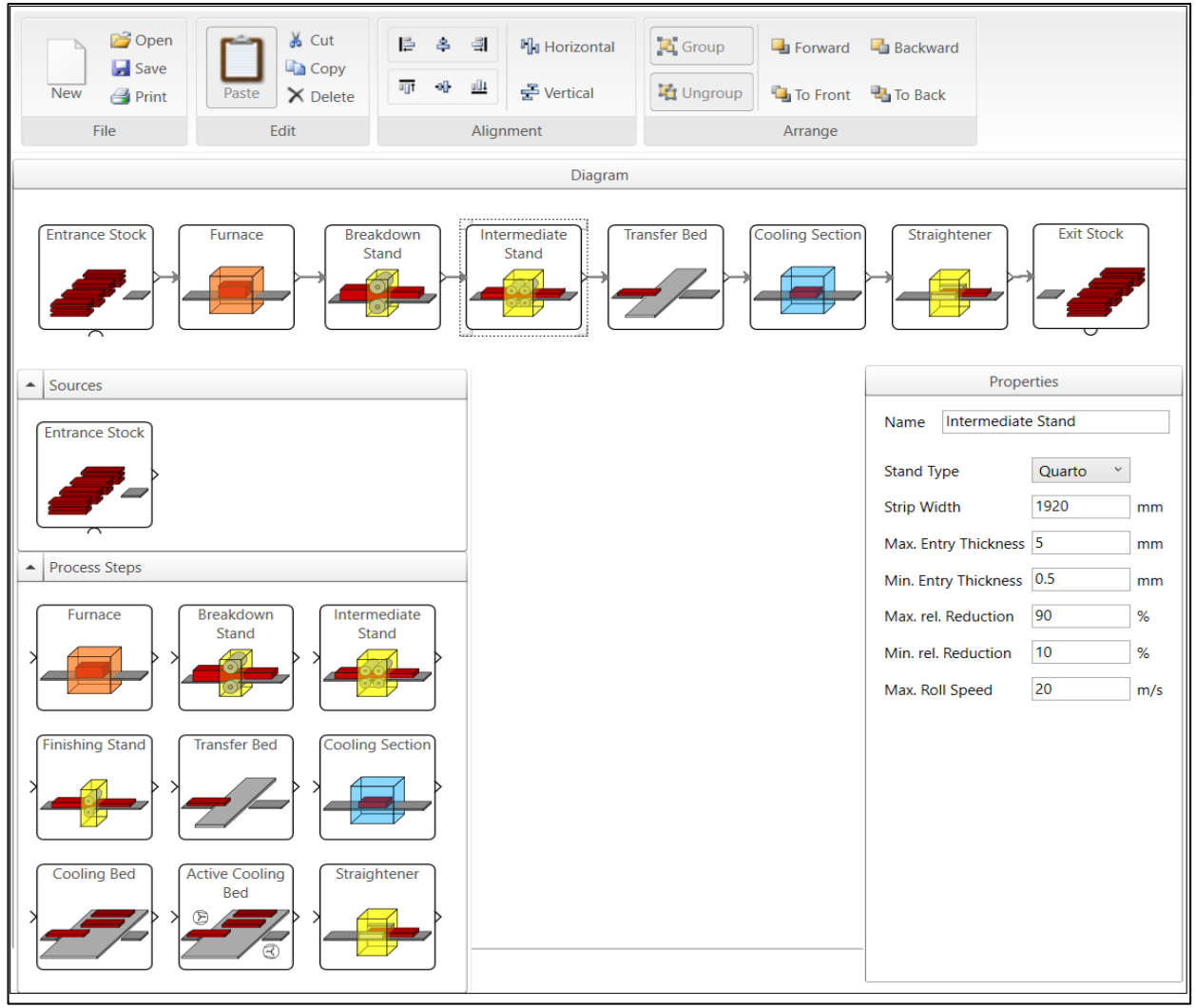
Temperature	Property Value
0	430
100	500
200	540
300	580
400	620
500	690
600	780
650	780





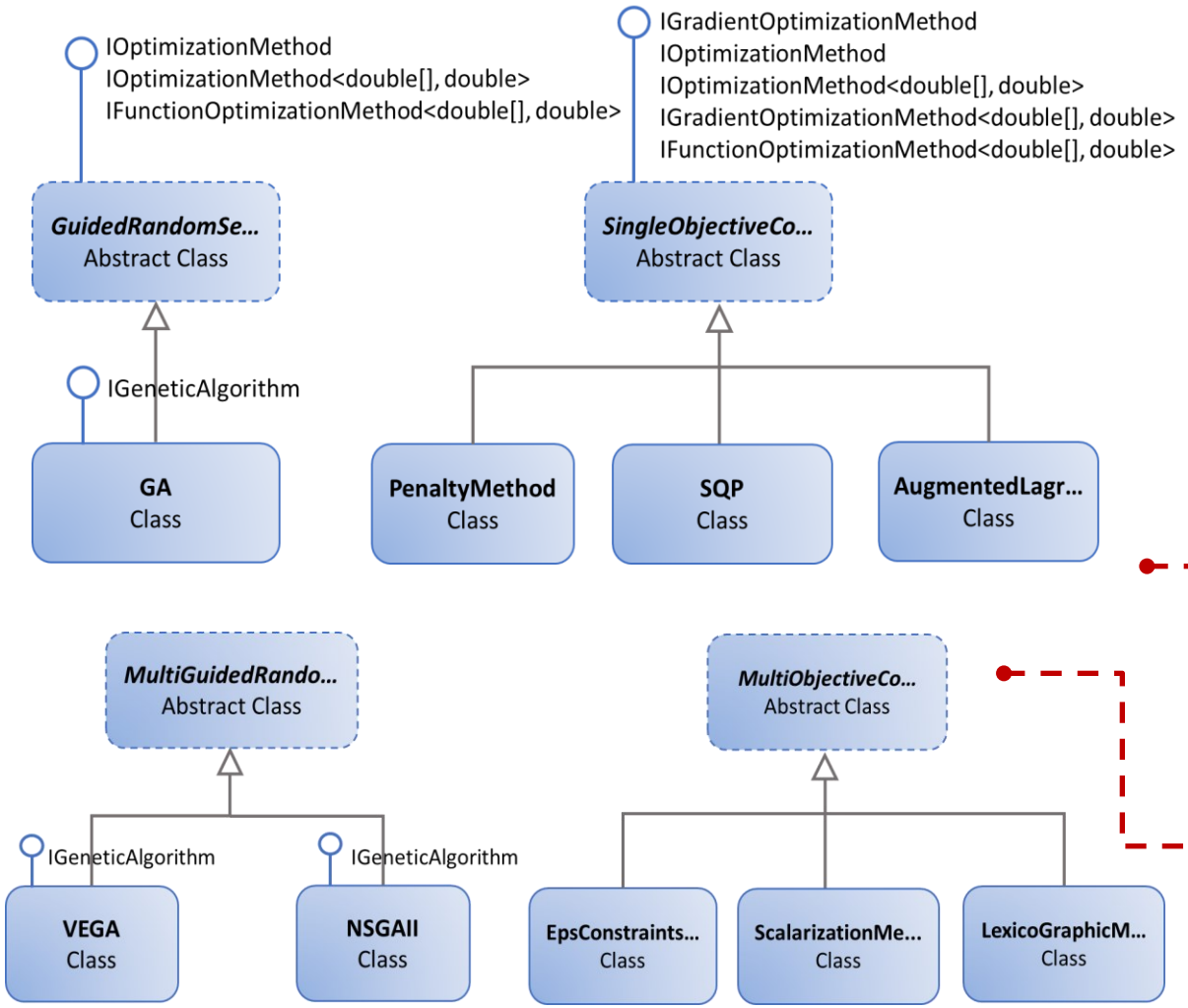
Properties

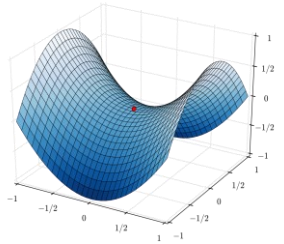
Name	Breakdown Stand	
Stand Type	Quarto	
Strip Width	1920	mm
Max. Entry Thickness	5	mm
Min. Entry Thickness	0.5	mm
Max. rel. Reduction	90	%
Min. rel. Reduction	10	%
Max. Roll Reduction	20	m/s



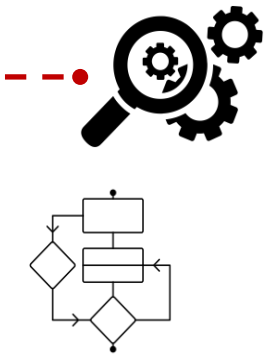
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Application-Oriented CPPOS Architecture Design: Optimization Module





Single or **multi-objective** optimization functions, subjected to inequality and equality constraints



Numerical Methods (Penalty function method, SQP, etc.) and **Guided Random Search Algorithms** (GA, PSO, etc.)

Implementation through **open-source libraries** of .Net Framework

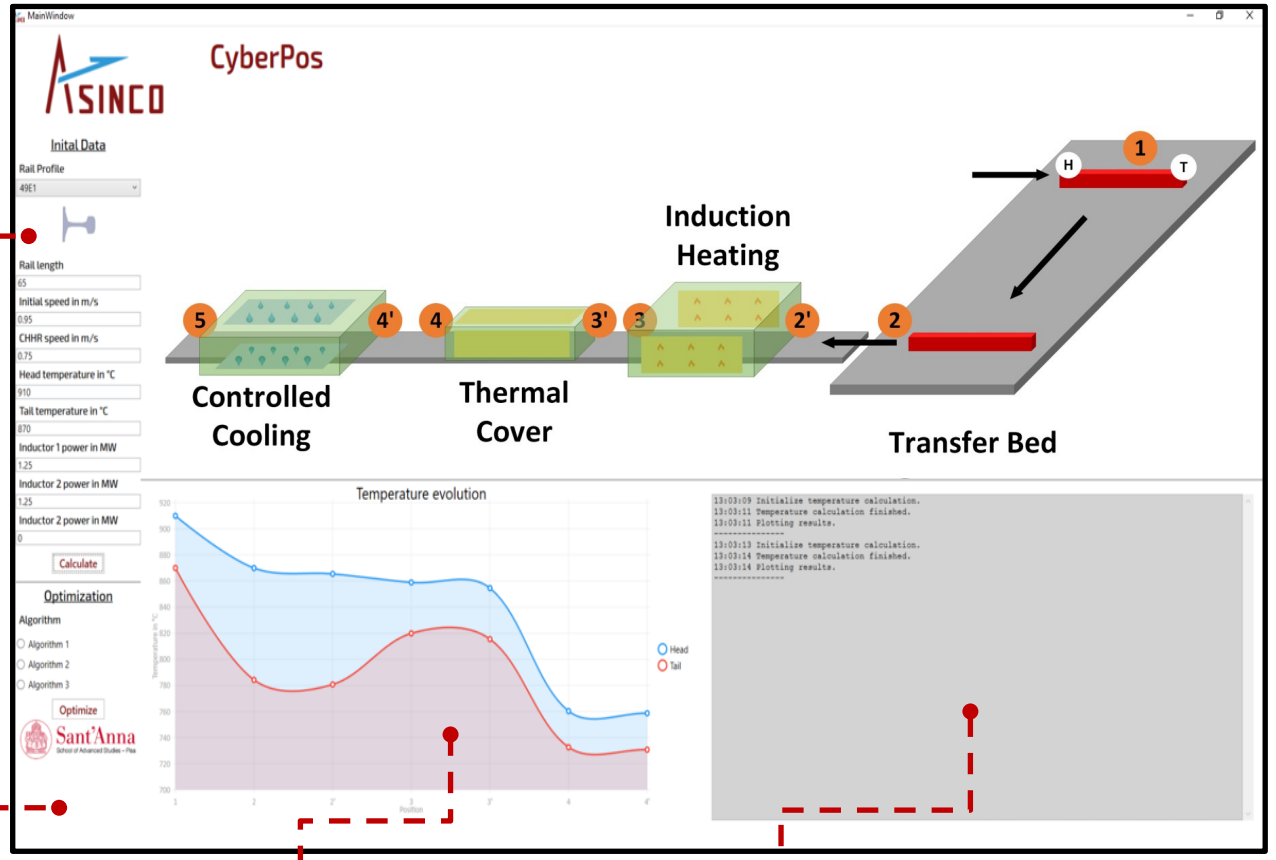
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Application-Oriented CPPOS Architecture Design: HMI Module

Product properties
Length
Temperature

Processes Input
Inductors power
Waiting time at point 2
Speed from point 2’ to 4 and inside the Controlled Cooling

Optimization Algorithms
Genetic Algorithm
Penalty Method
SQP



Product Temperature Profiles (Head and Tail)

Simulation Results

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

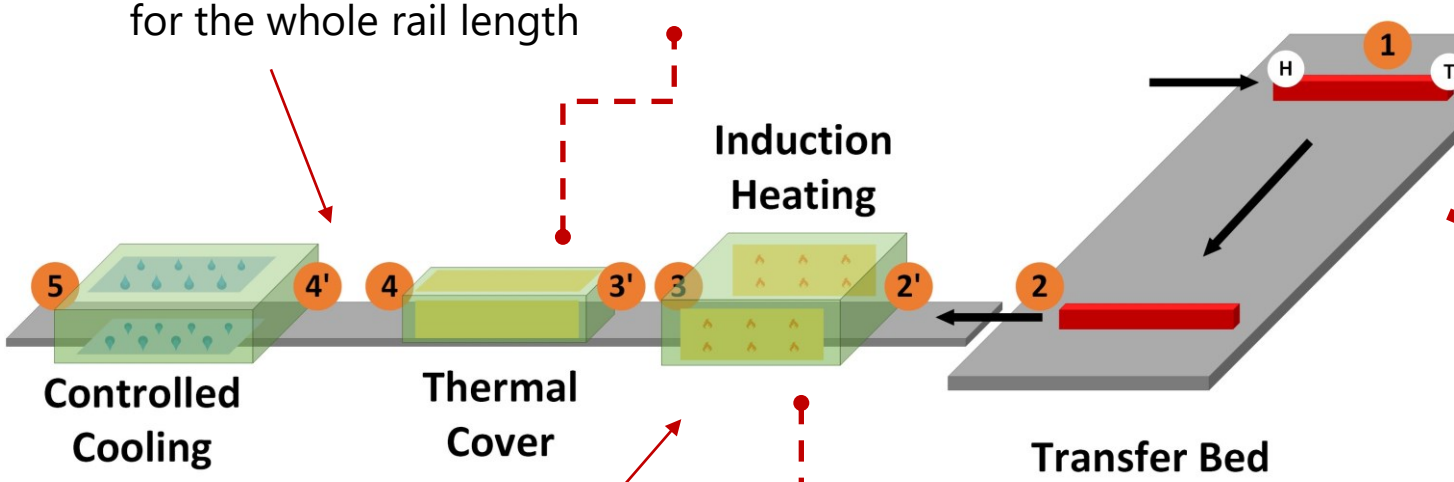
Induction-Heating System Use Case (ArcelorMittal Gijón, Spain)

Objective

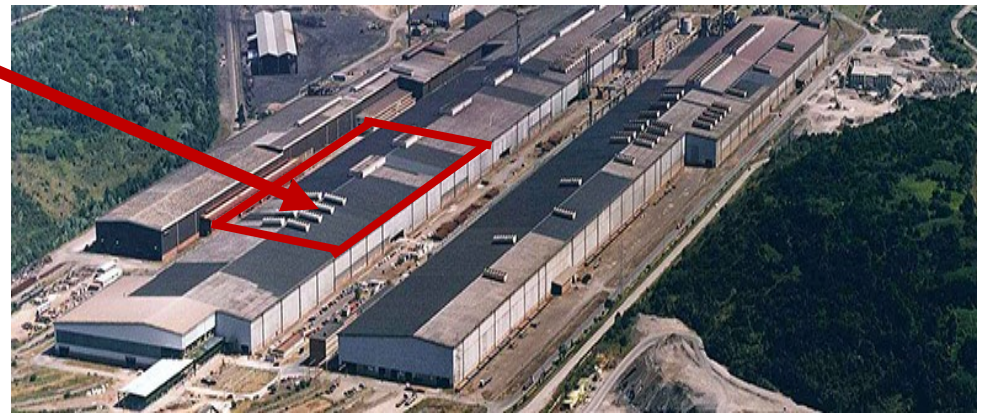
Reaching point 4' at a desired objective temperature, the same for the whole rail length

$$T_i = \frac{T_a}{A_{cover}} + \left(T_{i-1} - \frac{T_a}{A_{cover}}\right) e^{-\frac{k}{B_{cover}}\Delta t}$$

$$T_i = \frac{T_a}{A_{air}} + \left(T_{i-1} - \frac{T_a}{A_{air}}\right) e^{-\frac{k}{B_{air}}\Delta t}$$



ArcelorMittal



Constraints

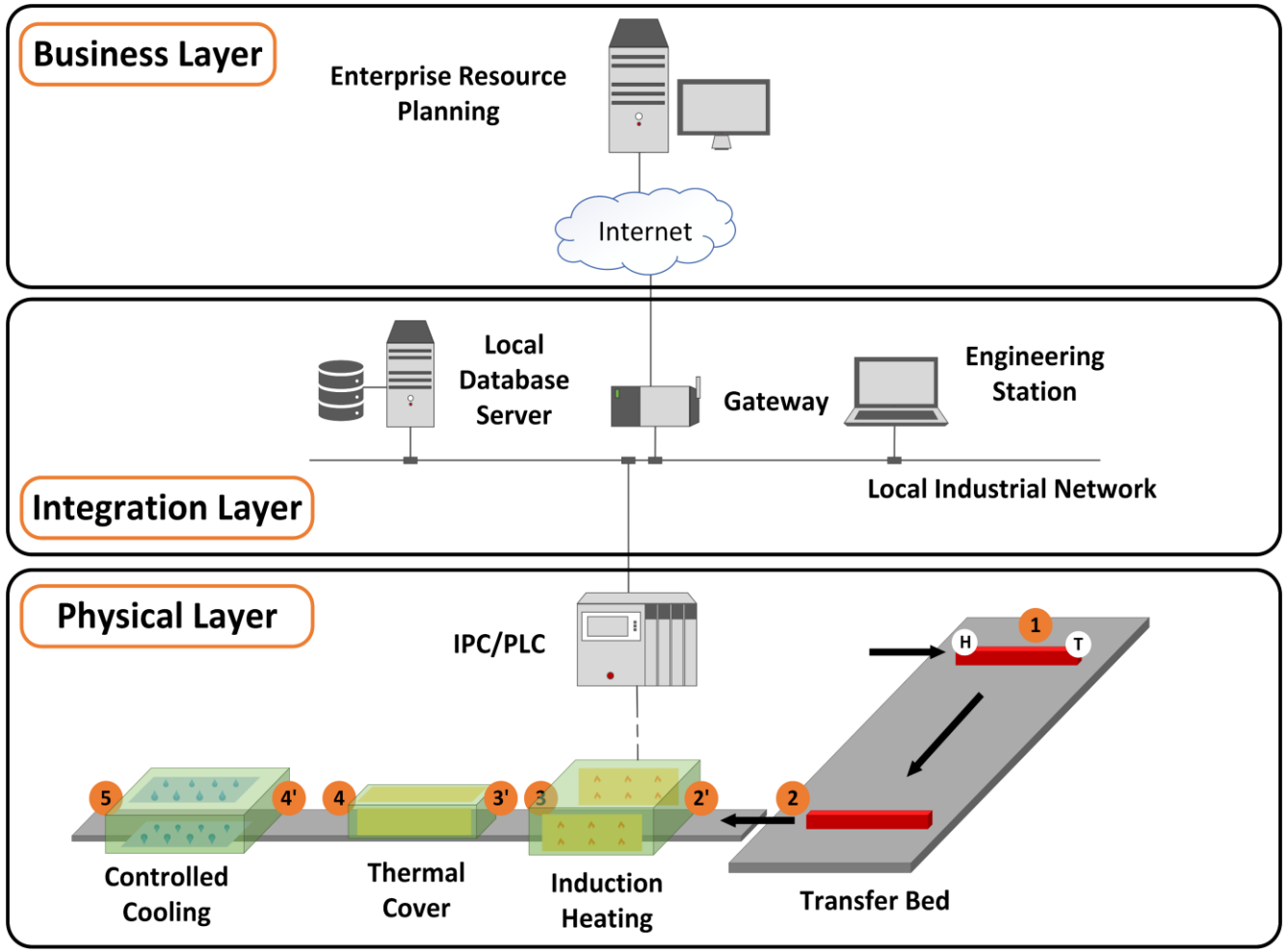
- ❑ Inductors power
- ❑ Temperature error tolerance

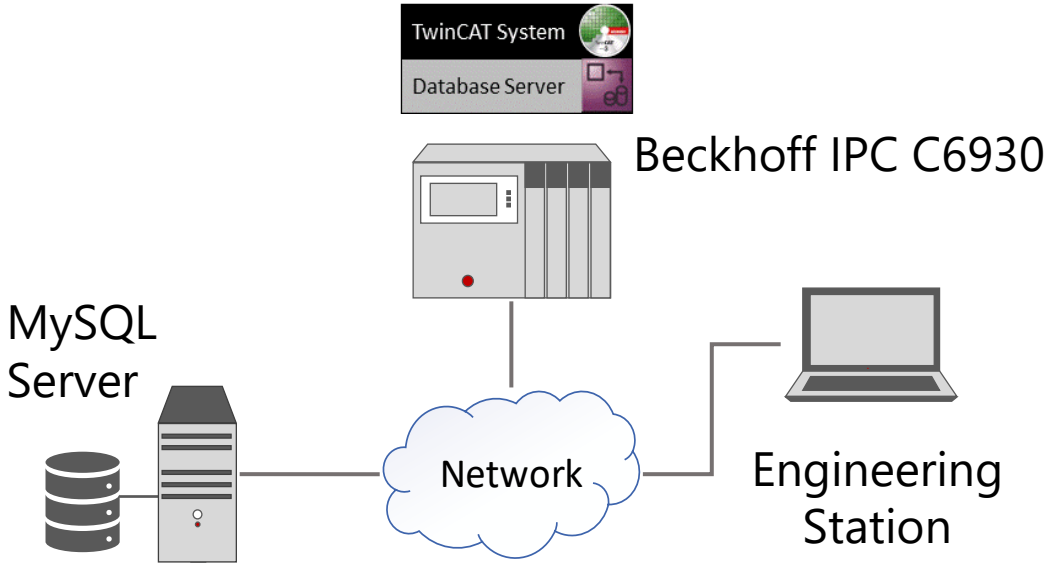
$$T_{i+1} = T_i + \frac{\Delta t}{C_{p,i}} \cdot \left[\frac{1}{\sigma_i(\overline{K}_n)} \cdot \left(\sqrt{\sigma_i(\overline{K}_n)\omega_i(\overline{K}_n)} - 0{,}5\right) - 2 \cdot \epsilon_R \cdot \left(1 + \frac{R}{l}\right) \cdot \left(T_i^4 - 1\right)\right]$$

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Superordinate Optimisation Platform: CPPOS Testbed Architecture

3-Layered Architecture for CPS

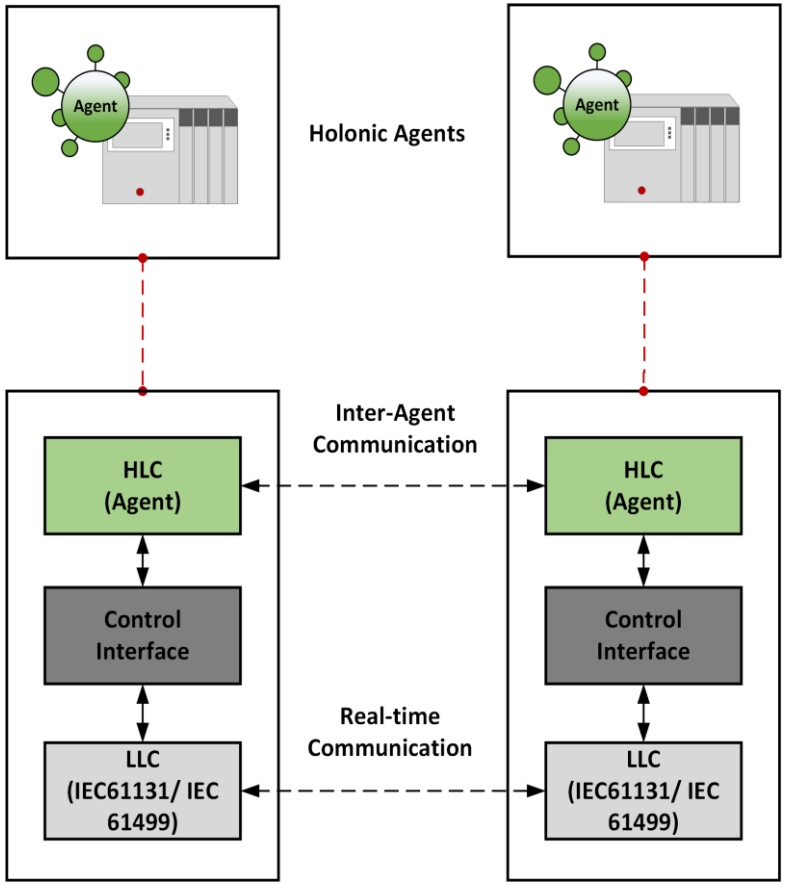


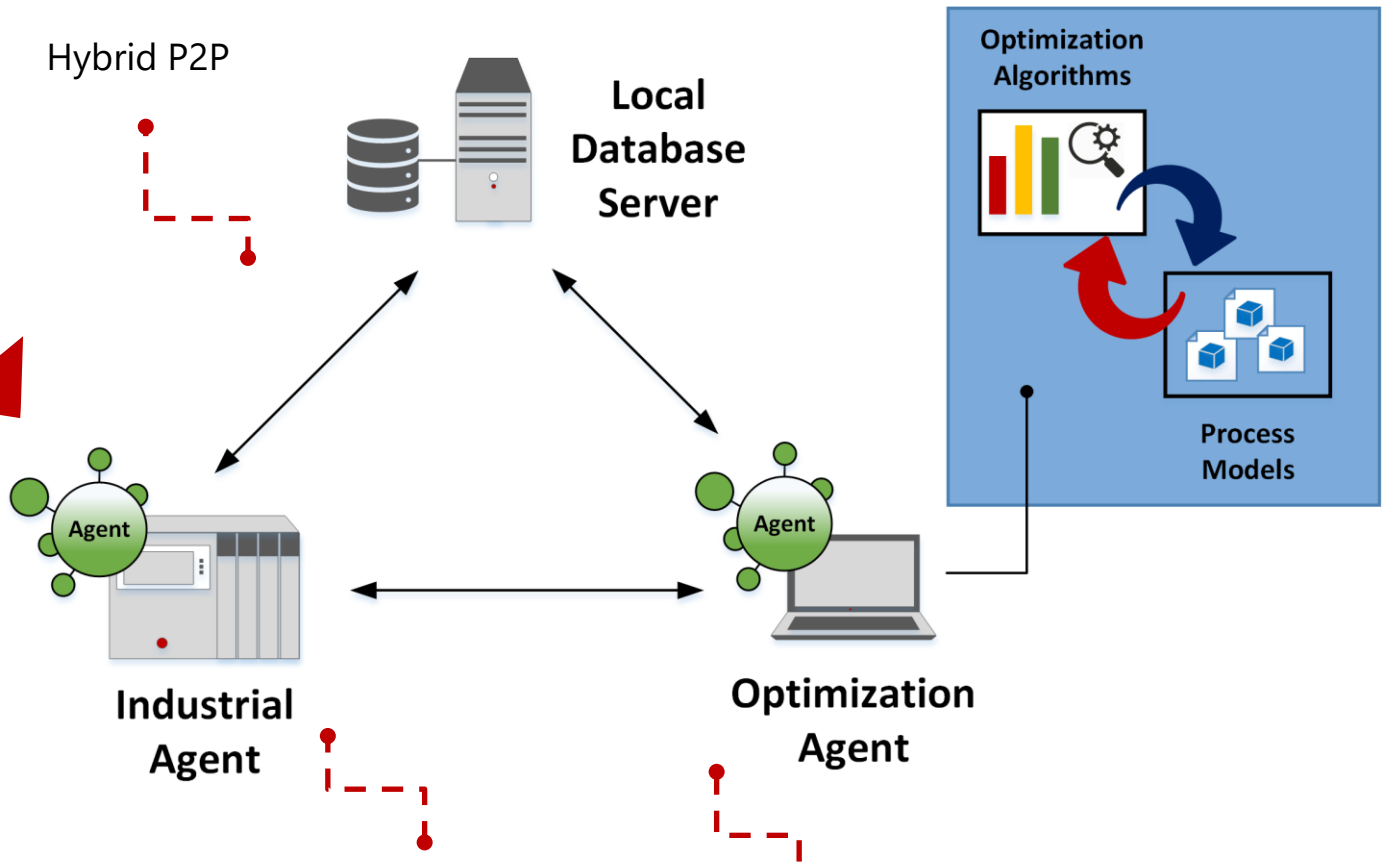


- TwinCAT 3 XAE (eXtended Automation Engineering)
- TwinCAT Database Server
- Visual Studio 2017 Environment
- TwinCAT ADS .Net library
- MySQL library
- External Database Server with MySQL 5.7

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Industrial Agent-Based Setup Strategy for the CPPOS Testbed





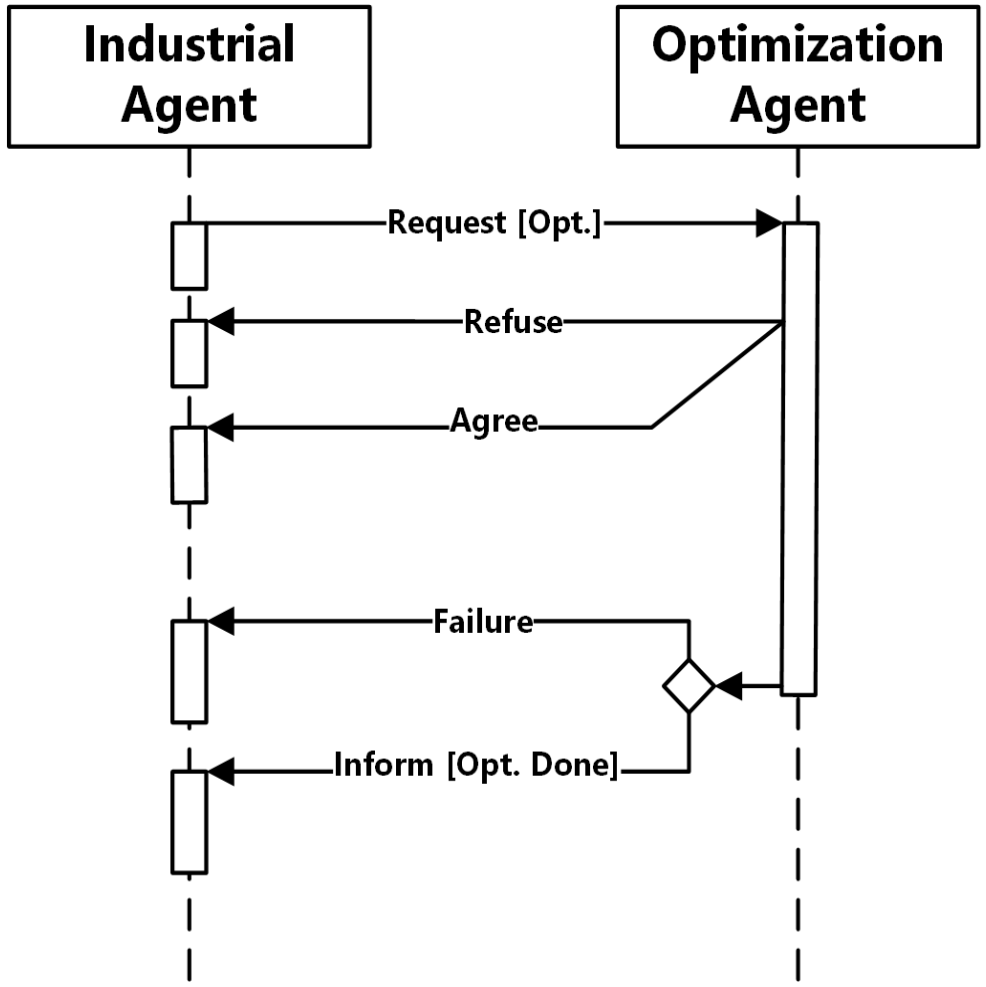
It is an agile and robust software entity that intelligently represents and manages the functionalities and capabilities of the PLC

It is responsible for the optimization tasks

[*] V. Iannino, J. Denker and V. Colla, "An Application-Oriented Cyber-Physical Production Optimisation System Architecture for the Steel Industry," *IFAC-PapersOnLine*, vol. 55, no. 2, pp. 60-65, 2022

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Industrial Agent-Based Setup Strategy for the CPPOS Testbed



- A protocol based on the **Request Interaction Protocol** of **FIPA** has been used to coordinate the optimization tasks.

- The protocol starts when the Industrial Agent requests the optimization of the process parameters, i.e. the inductors power, to the Optimization Agent based on the product target properties desired, i.e. the desired target temperature.

- The Optimization Agent uses Cyber-Twins for the simulation of the processes and for the through-process optimization.
  - ❑ It sends an *Inform* if it successfully completes the request indicating that the optimization is done otherwise a failure message.
  - ❑ It stores the results of the optimization into the database connected to the local industrial network and accessible to both agents.

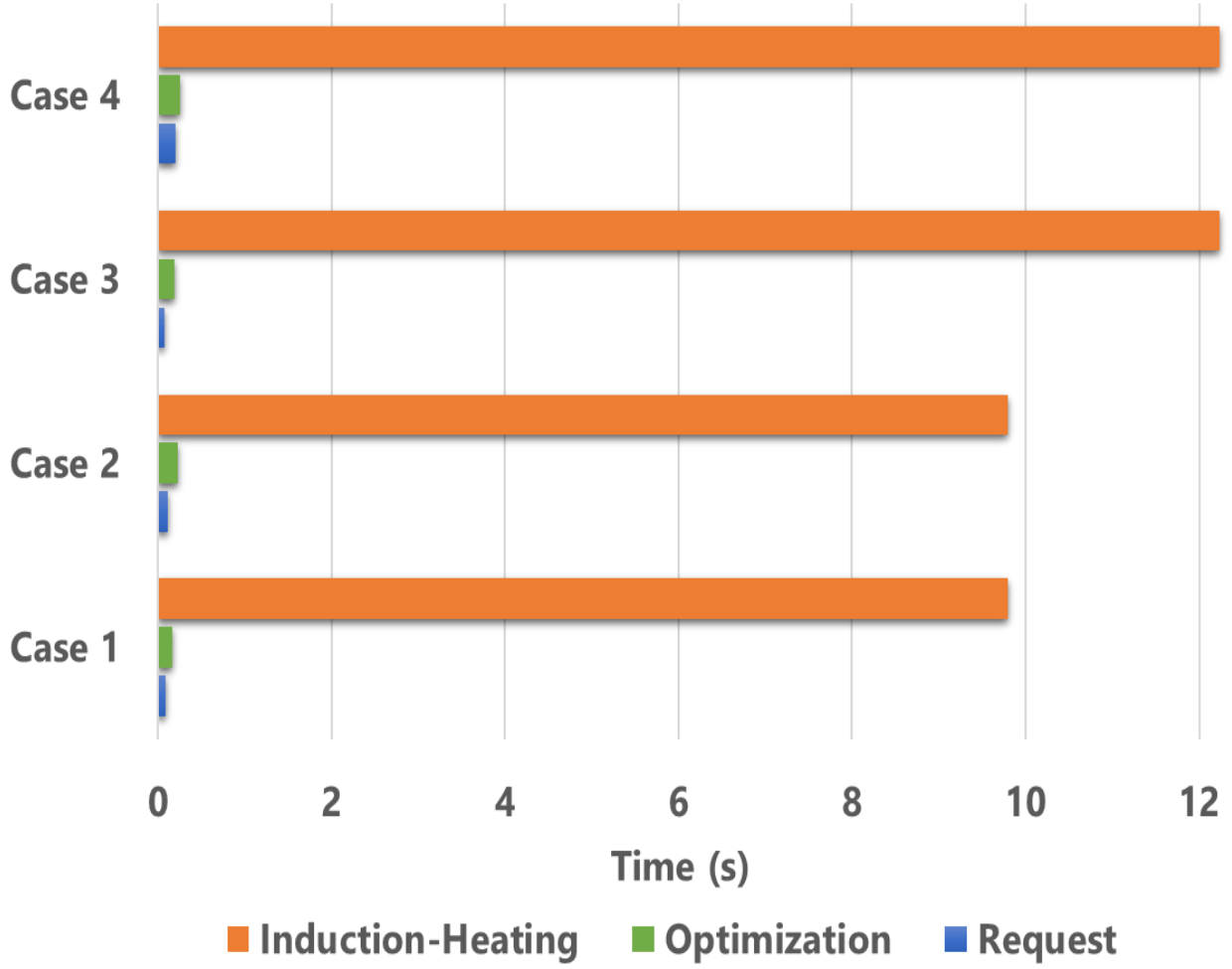
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Industrial Agent-Based Setup Strategy for the CPPOS Testbed: Simulation Experiments

$$\begin{cases} min\,\frac{1}{2}\left(T_{4'} - \bar{T}_{4'}\right)^2 \\ 0 \le P_{i_1} \le P_{max} \\ 0 \le P_{i_2} \le P_{max} \\ P_{i_1} = P_{i_2} \end{cases}$$

Input Parameters	
T_1	820 °C - 870 °C
$\bar{T}_{4'}$	700 °C - 710 °C
P_{max}	2 MW

- Optimization problem solved through GA and by integrating different thermo-process models.
- Typical process parameters are considered.
- Four different product profiles tested.
- The optimization performed by the Optimization Agent is fast and satisfies the problem constrains with a margin of error null or negligible in reaching the target temperature.



Conclusions

CPPS are the fundamental component of Industry 4.0 and enable new generation of smart processes

Few practical implementations of CPPS architectures are still available, especially in the steel sector

A concrete implementation of a CPPS architecture focused on the optimization of long products has been tested in an industrial perspective through a real testbed by investigating and exploiting an agent-based technology solution

Industrial agents have been used to realize CPS and to enable creation and interaction of cyber-physical components taking into account legacy systems typical of the steel sector

The combination of agent-based and CPS technologies is very promising and represents a realistic solution for the set of steel industrial challenges. Their systematic use in the steel sector may optimize the production processes increasing their efficiency

The smooth introduction of agent-based CPS in steel production systems by testing and demonstrating the technology through simulation tools and prototypes may be the solution to address concerns and doubts from industrial side

Acknowledgement

Part of this work was developed within the project entitled "*Virtual Design of Cyber-Physical Production Optimization Systems for Long Production Factories (Cyber-POS)*" (G.A. No 709669), which was funded by Research Fund for Coal and Steel (RFCS) of the European Union (EU). The sole responsibility of the issues treated in the presentation lies with the authors; the Commission is not responsible for any use that may be made of the information contained therein. We wish to acknowledge with thanks the EU for the opportunity granted that has made possible the development of the present work. We also wish to thank all partners of the project for their support and the fruitful discussion that led to successful completion of the present work.

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