INSTITUTE OF COMMUNICATION, INFORMATION AND PERCEPTION TECHNOLOGIES

Sant'Anna School of Advanced Studies – Pisa

ICT COISP

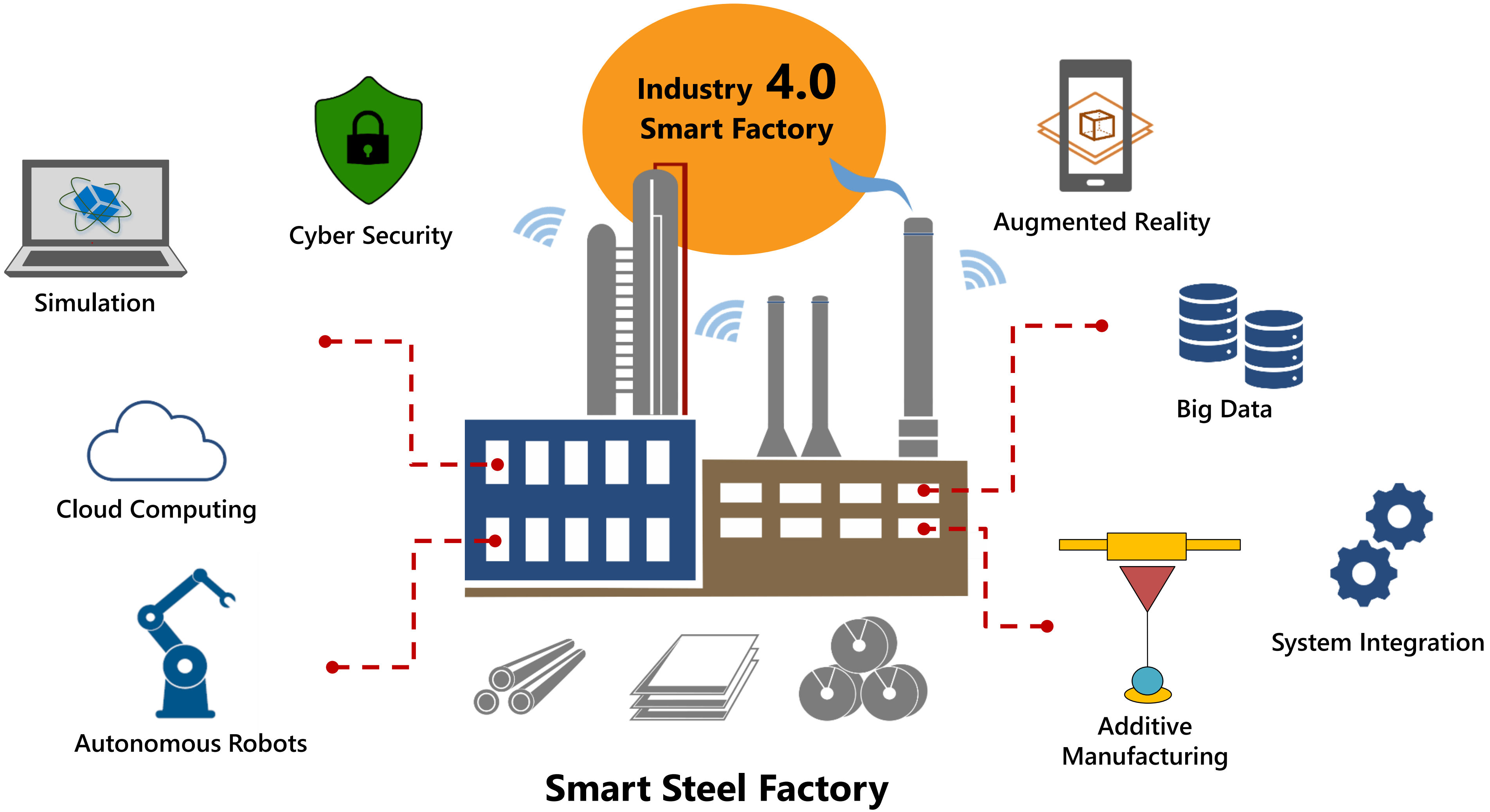
Information and Communication Technologies for Complex Industrial Systems and Processes

Cyber-Physical Systems For Production Simulation And Optimization Within Complex Industrial Systems

Vincenzo Iannino, Valentina Colla

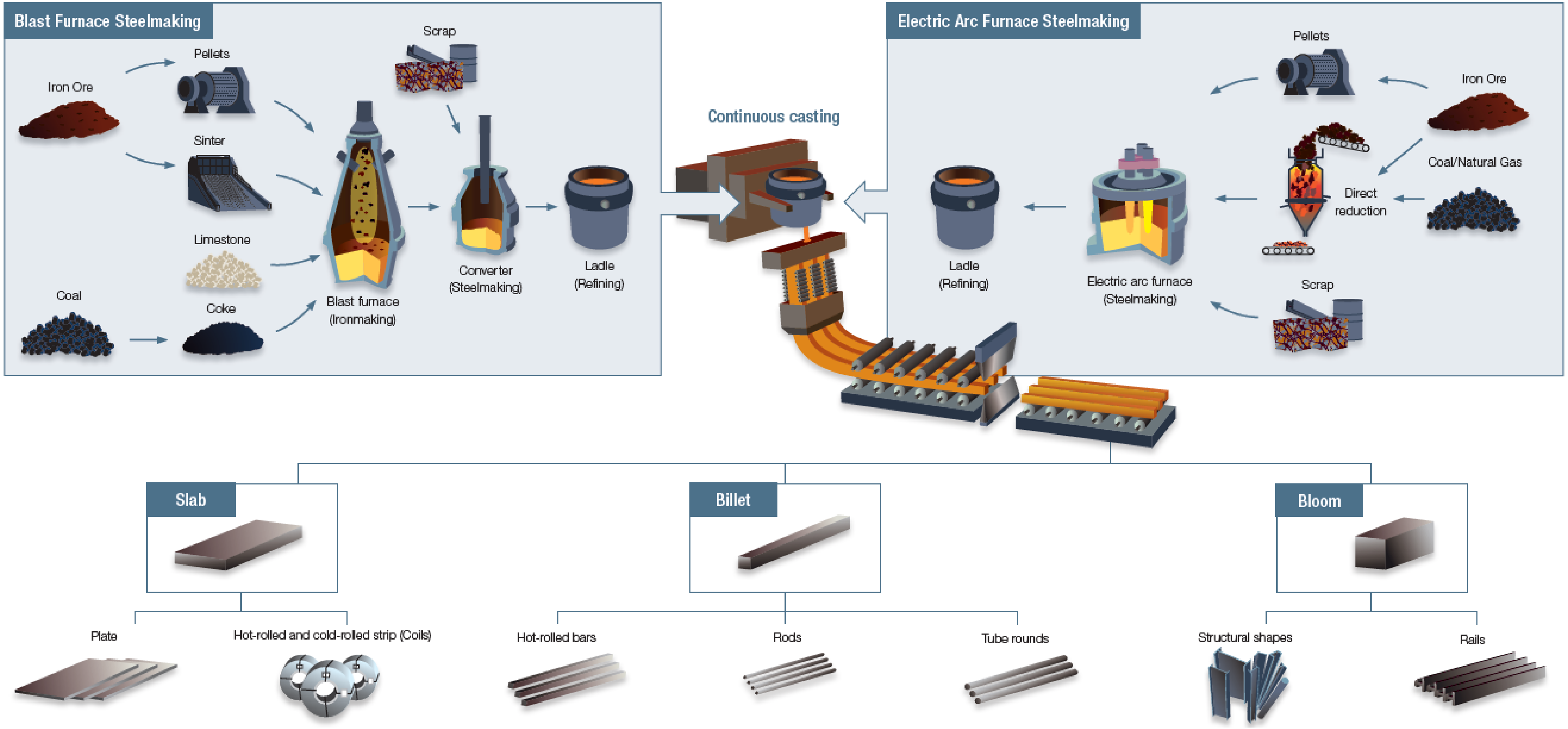
Steel Manufacturing Industries

The new era of Industry 4.0



Case Studies

Steel Manufacturing Context



*Source: World Steel Association

Case Studies

Steel Manufacturing Context: Features

Steelworks involve manifold and complex production steps, which are closely correlated and often seamlessly connected

Unexpected events are very common, which causes e.g., delays, waste of materials or off-spec products

Many of these production cycles are at least partly continuous

Each production step needs multiple resources

A variety of legacy systems needs to coexist in brownfield sectors

The steel industry is energy intensive

The automation structure is not flexible

Case Studies

Steel Manufacturing Context: Challenges

To enhance communication among subprocesses

To handle unexpected events within the process by promptly reacting to them and mitigating their effects

To improve the current process logistics and the adopted optimization solutions

To improve the allocation and efficient exploitation of plant resources

To support common IT infrastructures and legacy systems

To efficiently manage energy sources and energy carriers

To enable a smooth and economic viable transition towards I4.0 technologies

To attract and retain qualified personnel

Case Studies

Steel Manufacturing Context: Barriers

Control-centric view is deep-rooted inside companies

Most IT systems still rely on a ISA95-based pyramidal architecture

CPS- and MAS-based solutions and concepts may be hard to understand as well as their potential

For some sub-processes simulation models are still missing or lack in accuracy

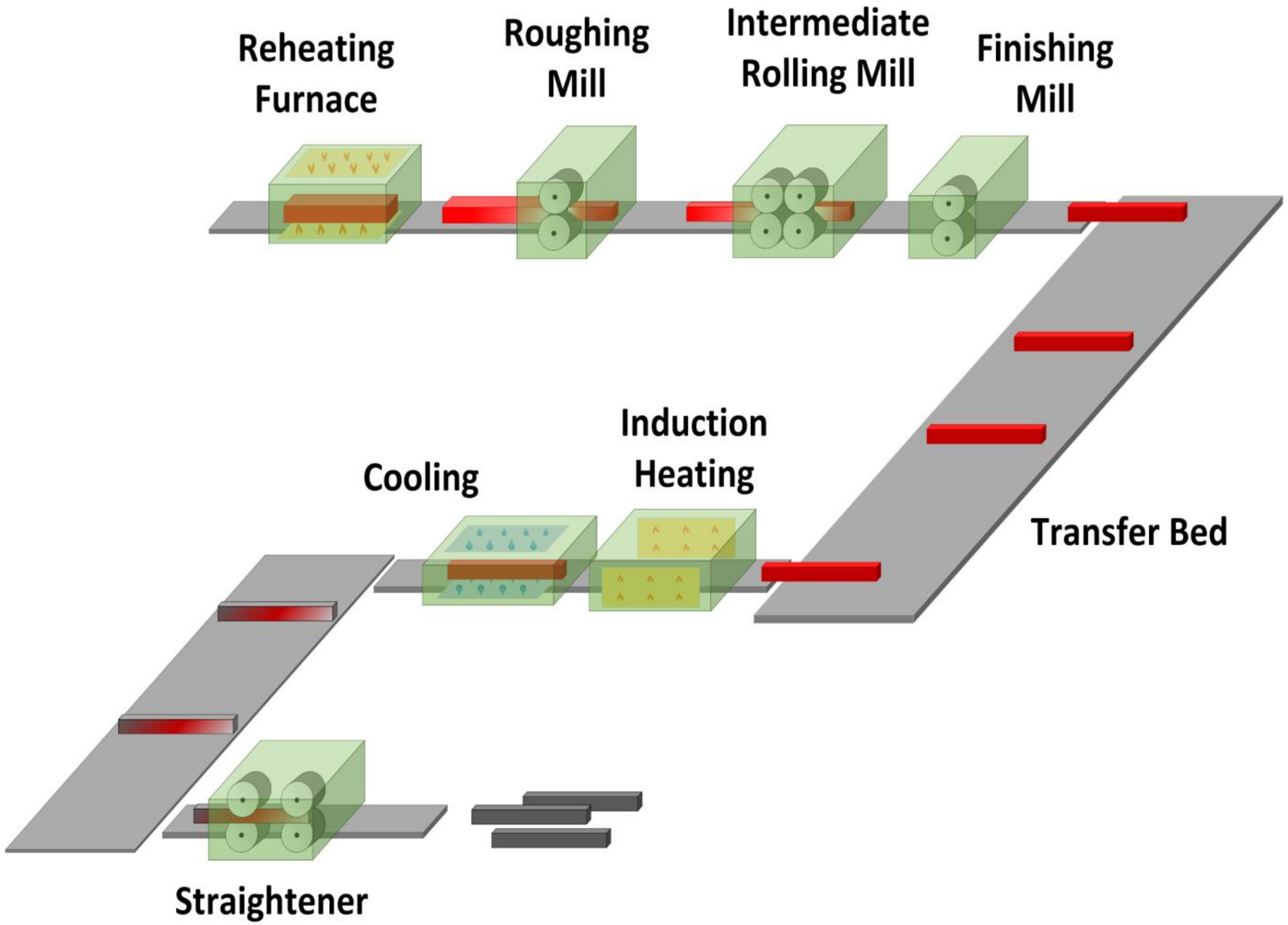
Skilled people, both workers and managers, and know how about new digital technologies are missing

A relevant age gap is also foreseen between workers currently employed and future employees

Lacks of internal management as driving force for implementing I4.0 projects

Case Studies

Long Products Manufacturing Processes



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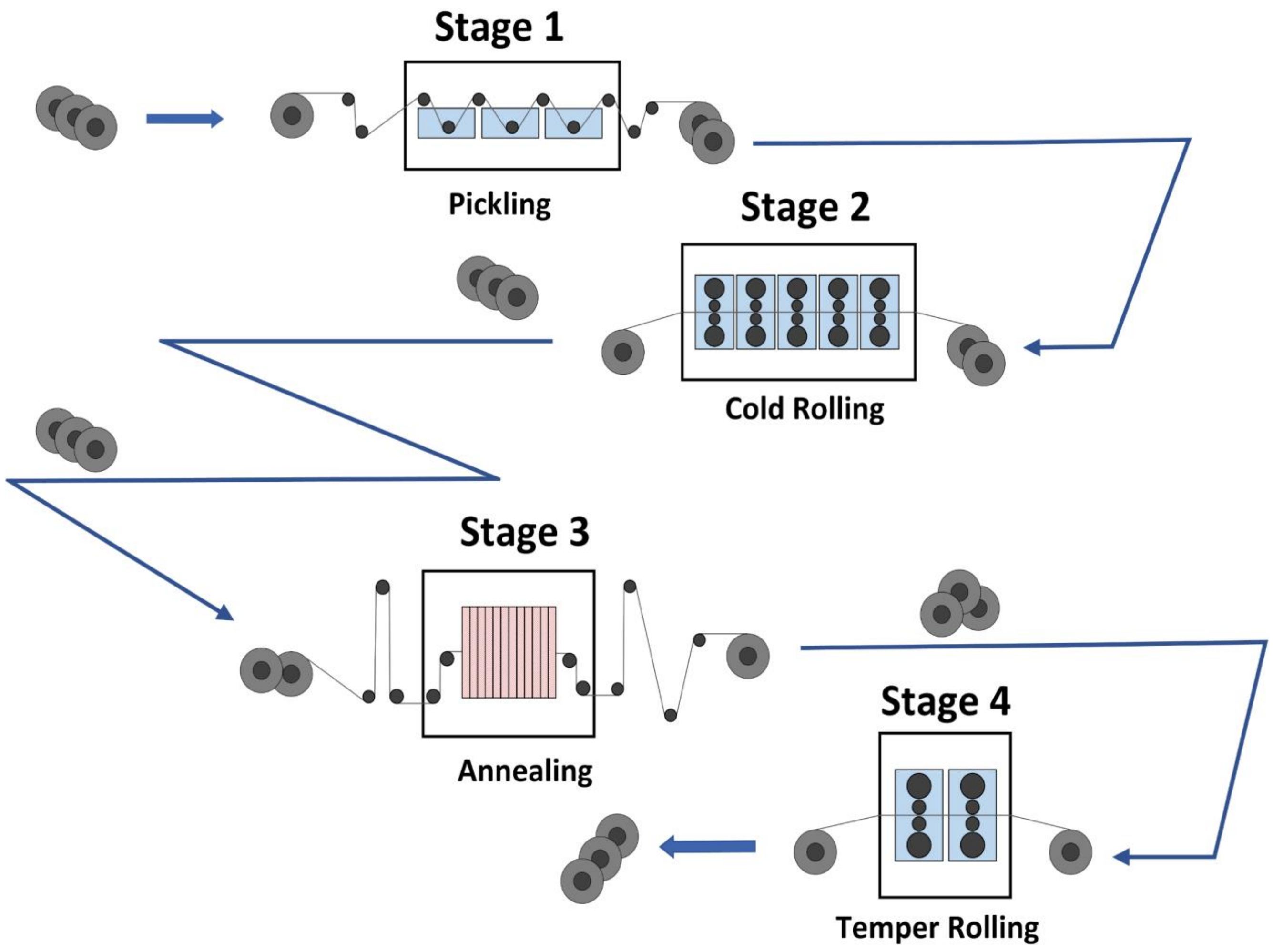
Case Studies

Flat Products Manufacturing Processes



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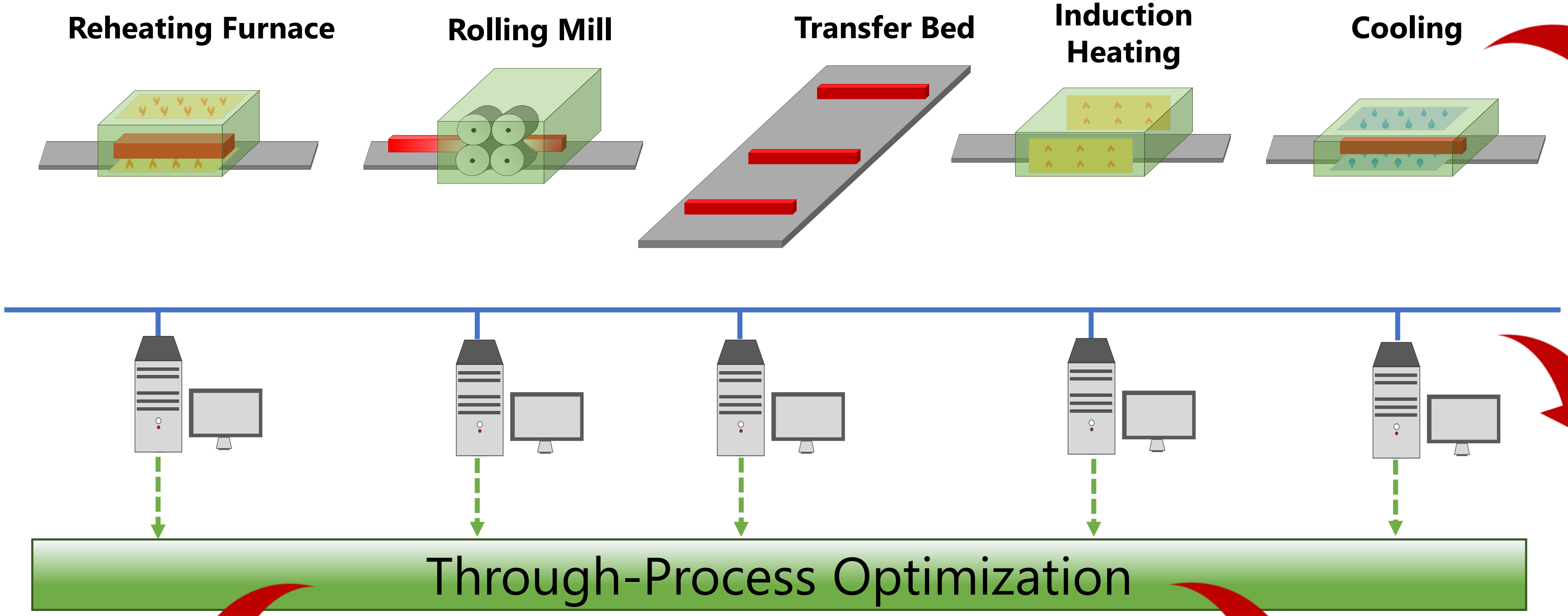
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories
Cyber-POS Project

Project name:
Virtual Design of Cyber-Physical Production Optimization Systems for Long Production Factories (Cyber-POS). The project started on July 1st 2016 and ended on December 31st 2019.

Objective:
Development of a virtual simulation platform for the design of cyber-physical production optimization systems for long production facilities, with special emphasis to process models, leading to decrease material and energy consumption, shortened production time and improved product quality.

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

The Need of Through-Process Optimization and CPS



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

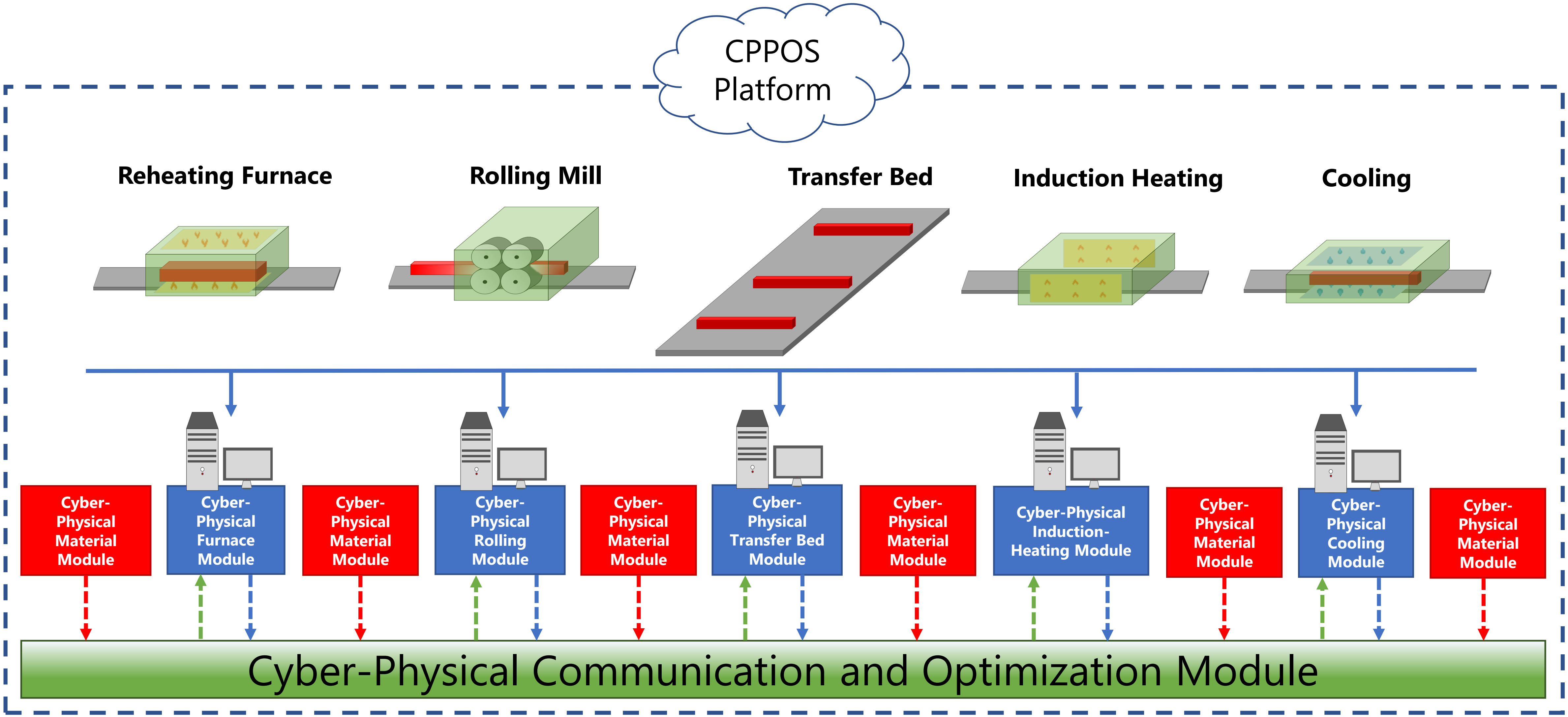
Missing of standardized interfaces between the aggregates

The traditional optimization focused only on individual process separately

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

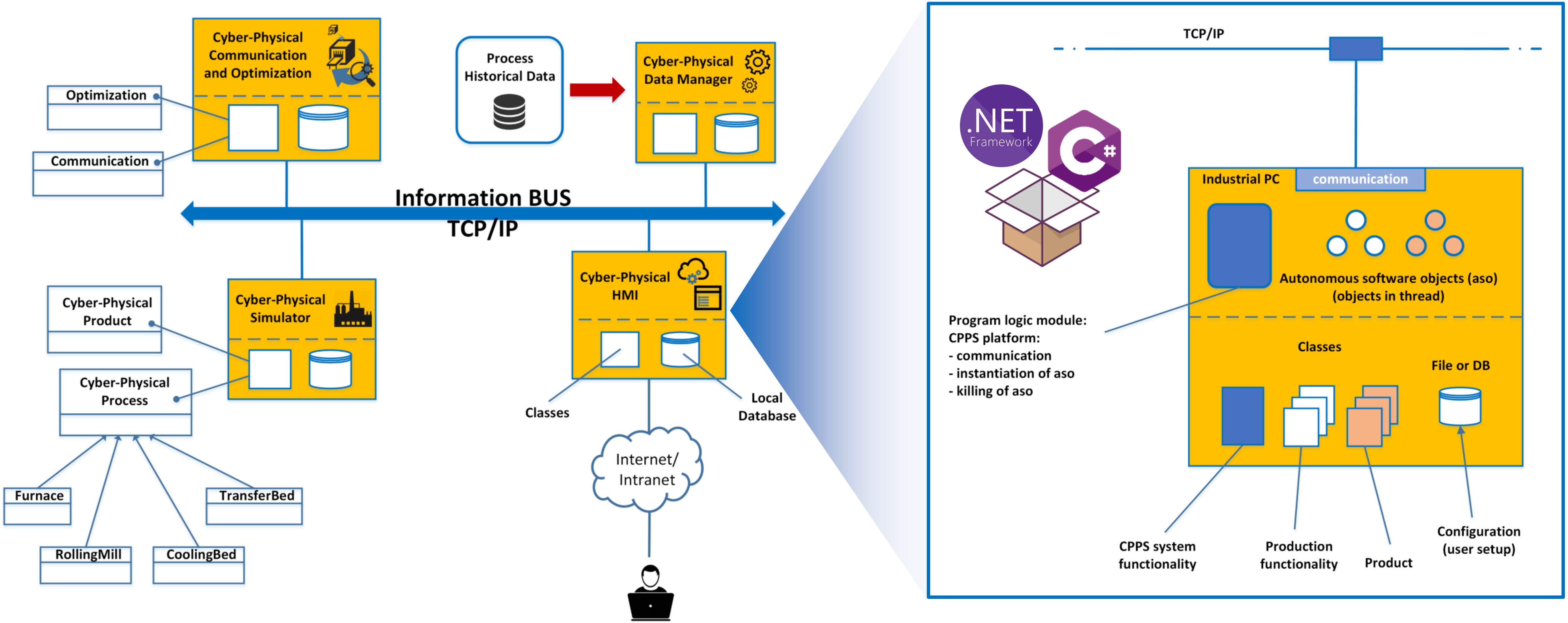
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

CPPOS Platform



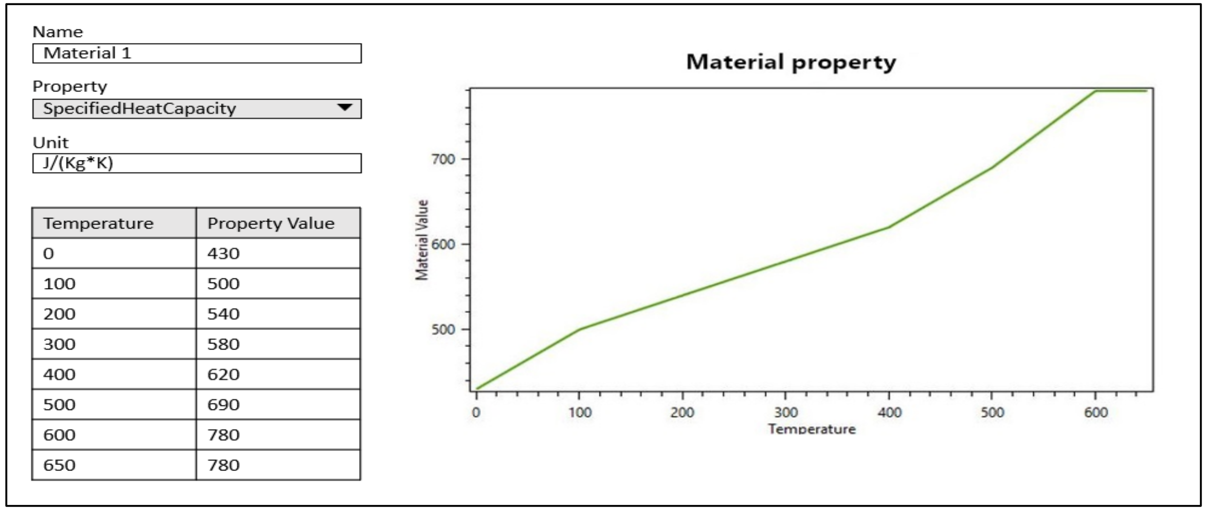
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

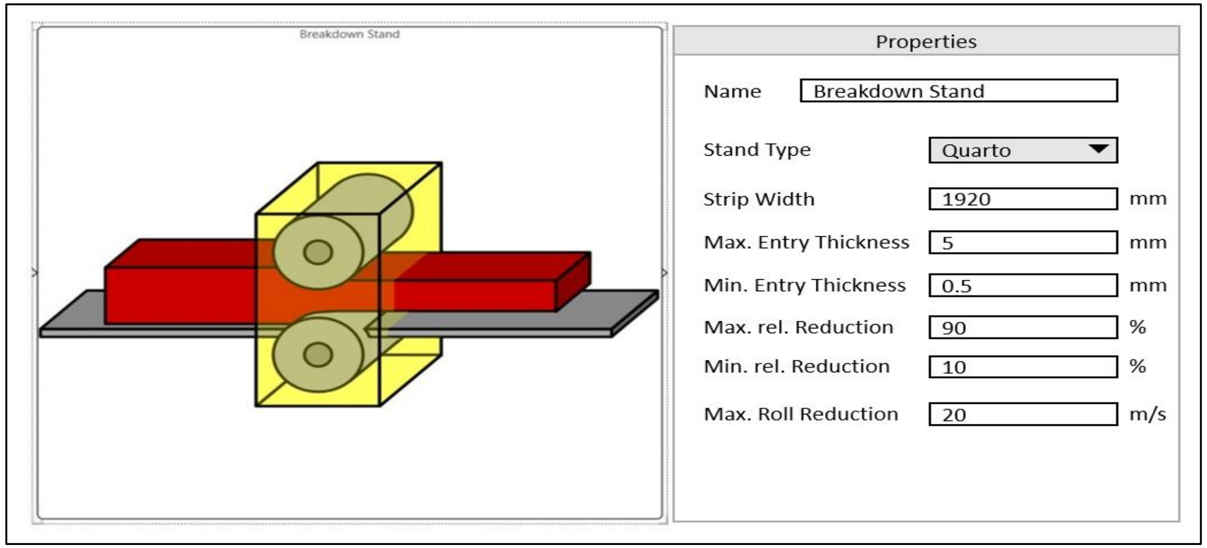
CPPOS Platform Architecture Design

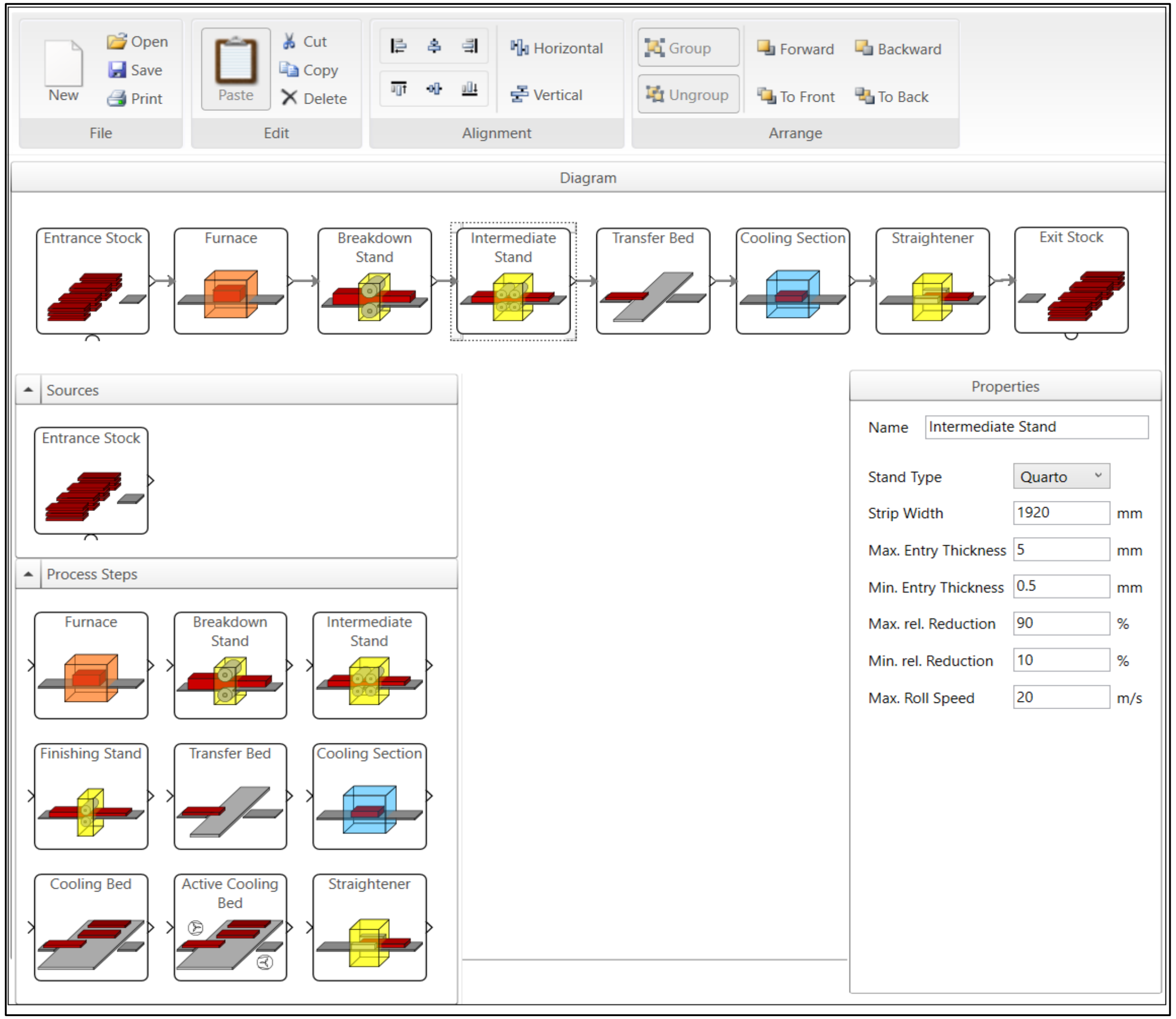


Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

CPPOS Platform Architecture Design: Product and Process Modules

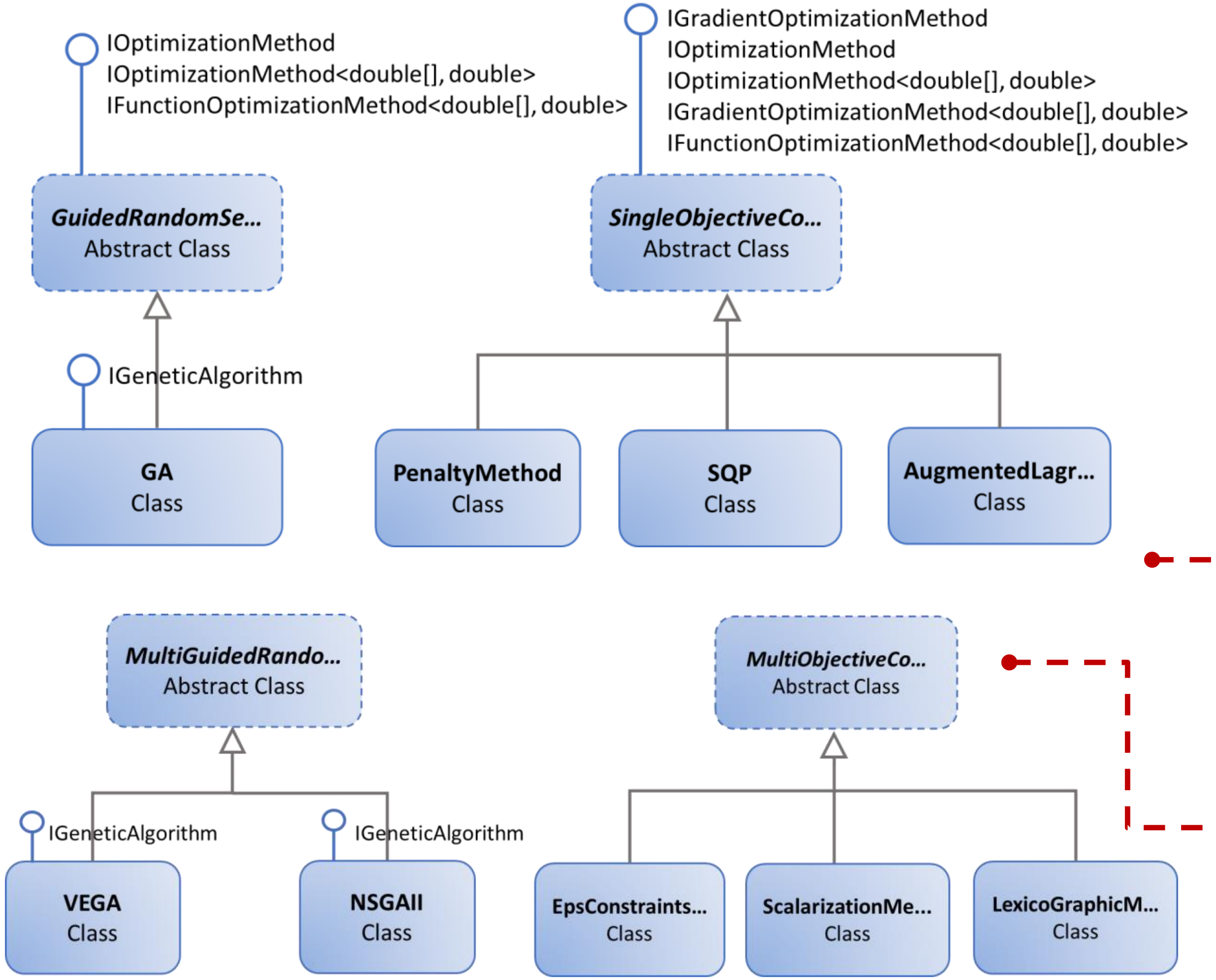


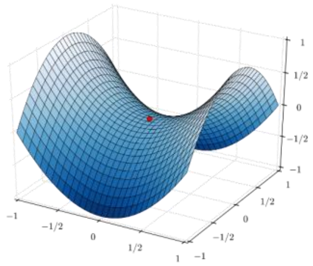




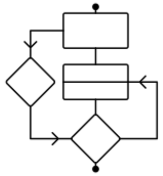
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

CPPOS Platform 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.)

Accord .NET Framework

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

GENETICSHARP

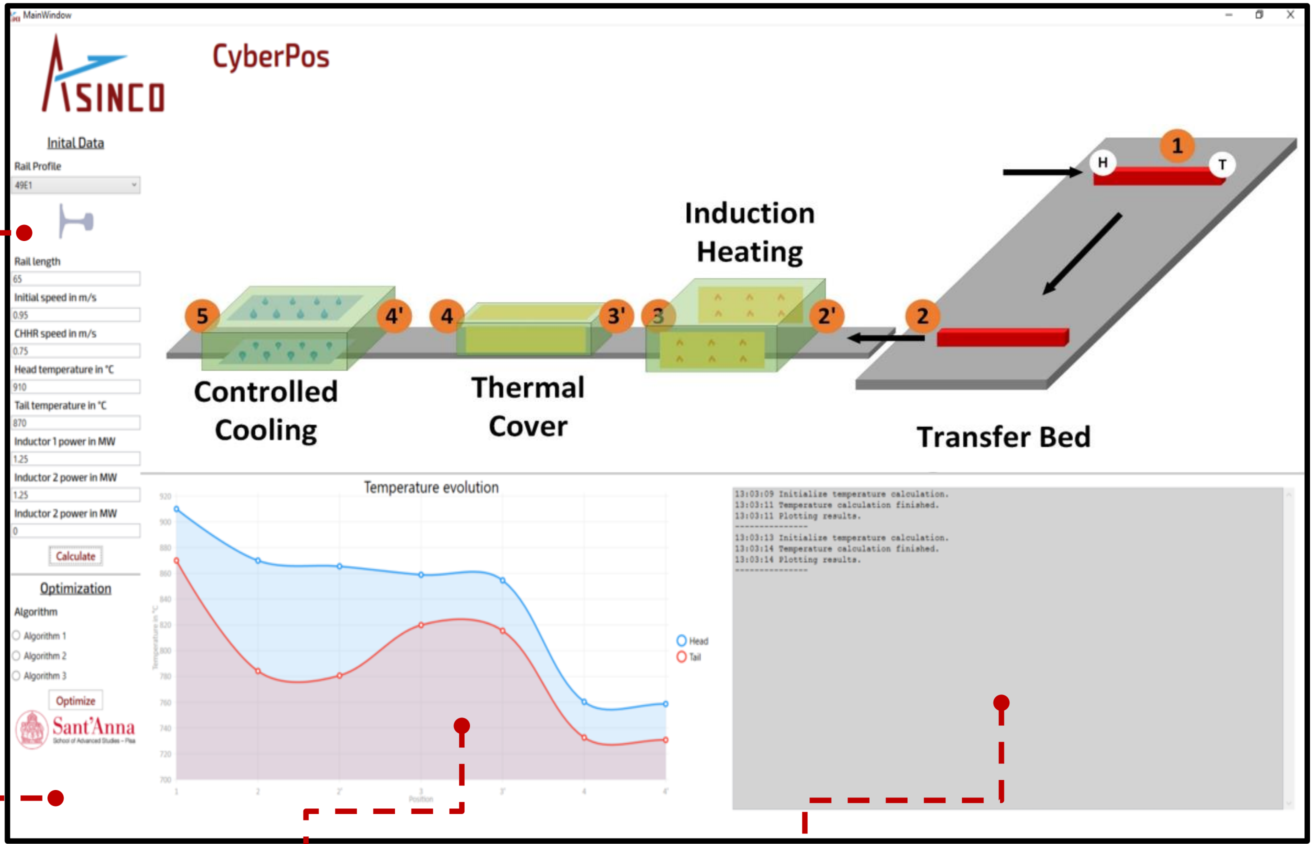
Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

CPPOS Platform Architecture Design: HMI Module

Rail 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



Rail 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)

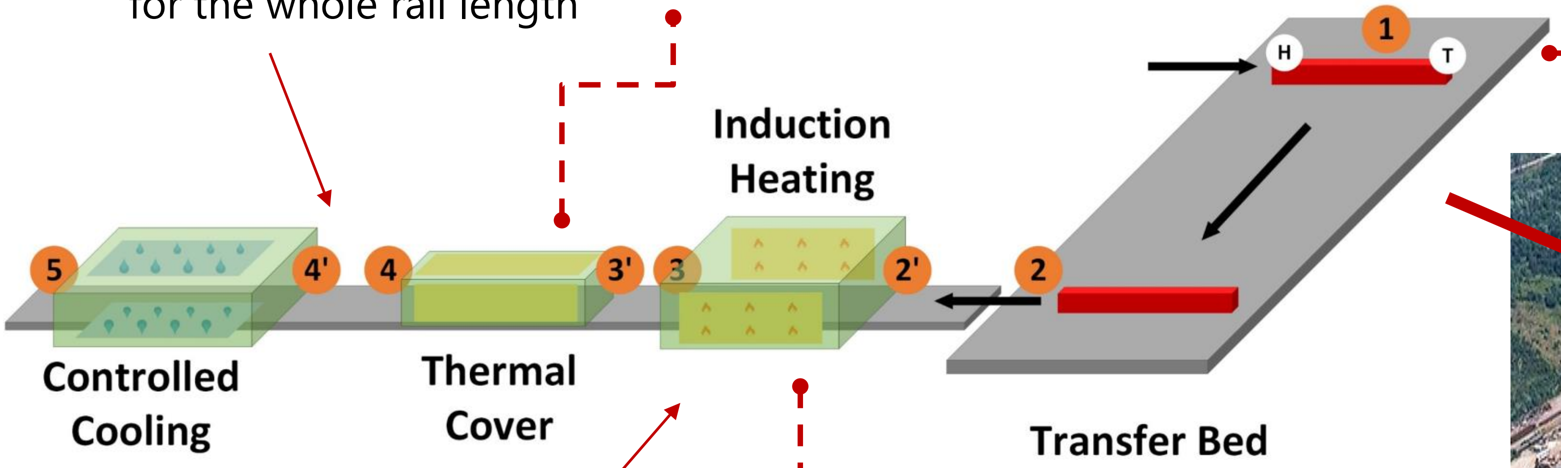
Objective

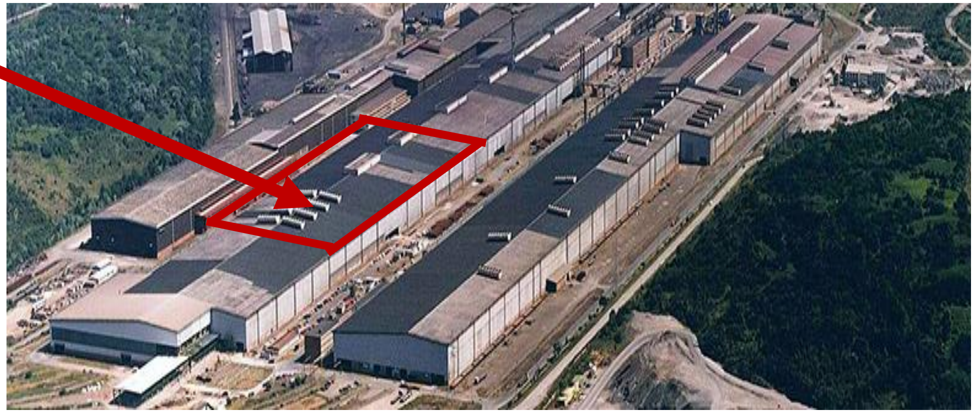
Reaching point 4′ at a desired objective temperature, the same for the whole rail length

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

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

ArcelorMittal





Constraints

- ❑ Inductors power
- ❑ Temperature error tolerance

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

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Induction-Heating System Optimization Results

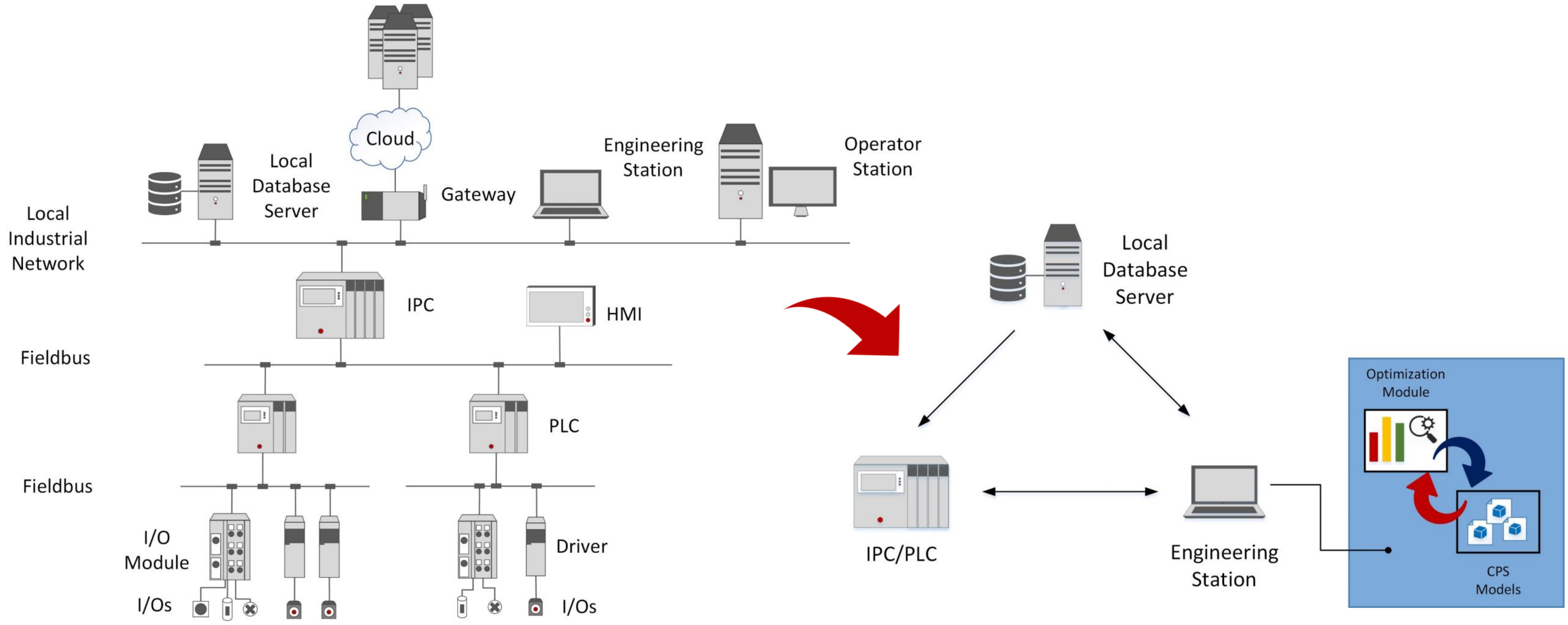
$$
\begin{cases}
\min E = \frac{1}{2}\left(T(4') - \overline{T}(4')\right)^2 \\
0 \leq P_1 \leq P_{max} \\
0 \leq P_2 \leq P_{max} \\
P_1 = P_2
\end{cases}
$$

Input Parameters	
$T(1)$	870 °C
$T(4')$	710 °C
P_{max}	2 MW

	Barrier (MATLAB)	GA (MATLAB)	Penalty (Opt. Module)	GA (Opt. Module)
μ_{P_1} (W)	0.4416	0.4417	0.4416	0.4416
σ_{P_1} (W)	0	0.0012	0	0
μ_{P_2} (W)	0.4416	0.4417	0.4416	0.4416
σ_{P_2} (W)	0	0.0013	0	0.0006
μ_E	0	0.0011	0	0.004
σ_E	0	0.01	0	0.001
τ_{av} (s)	0.02	3.66	0.05	0.16

Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

Testbed Architecture



Cyber-Physical Production Optimization Systems Platform for Long Steel Factories

DynReAct Project

Project name:

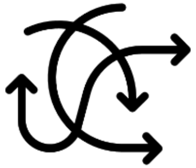
Refinement of production scheduling through dynamic product routing, considering real-time plant monitoring and optimal reaction strategies (DynReAct). The project started on June 1st 2019 and will end on December 31st 2022.

Objective:

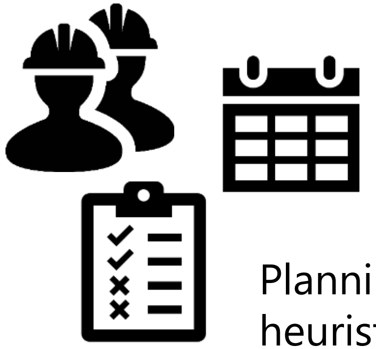
Improve flexibility of production scheduling in flat steel production through embedded real-time analytics of all available information coming from each plant involved and optimal scheduling.

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

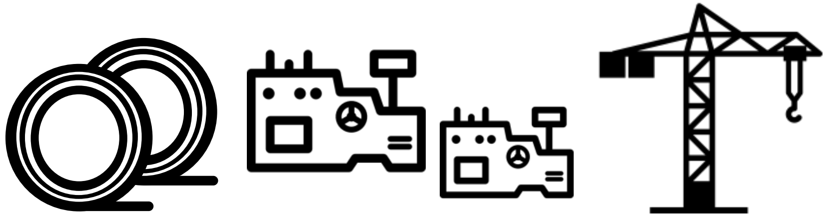
Flat Steel Production Scheduling



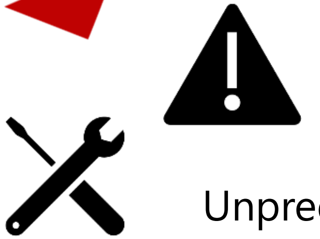
One of the most difficult and complex problem (NP-hard)



Planning system supported by heuristics, knowledge of planners and the analysis of order structure



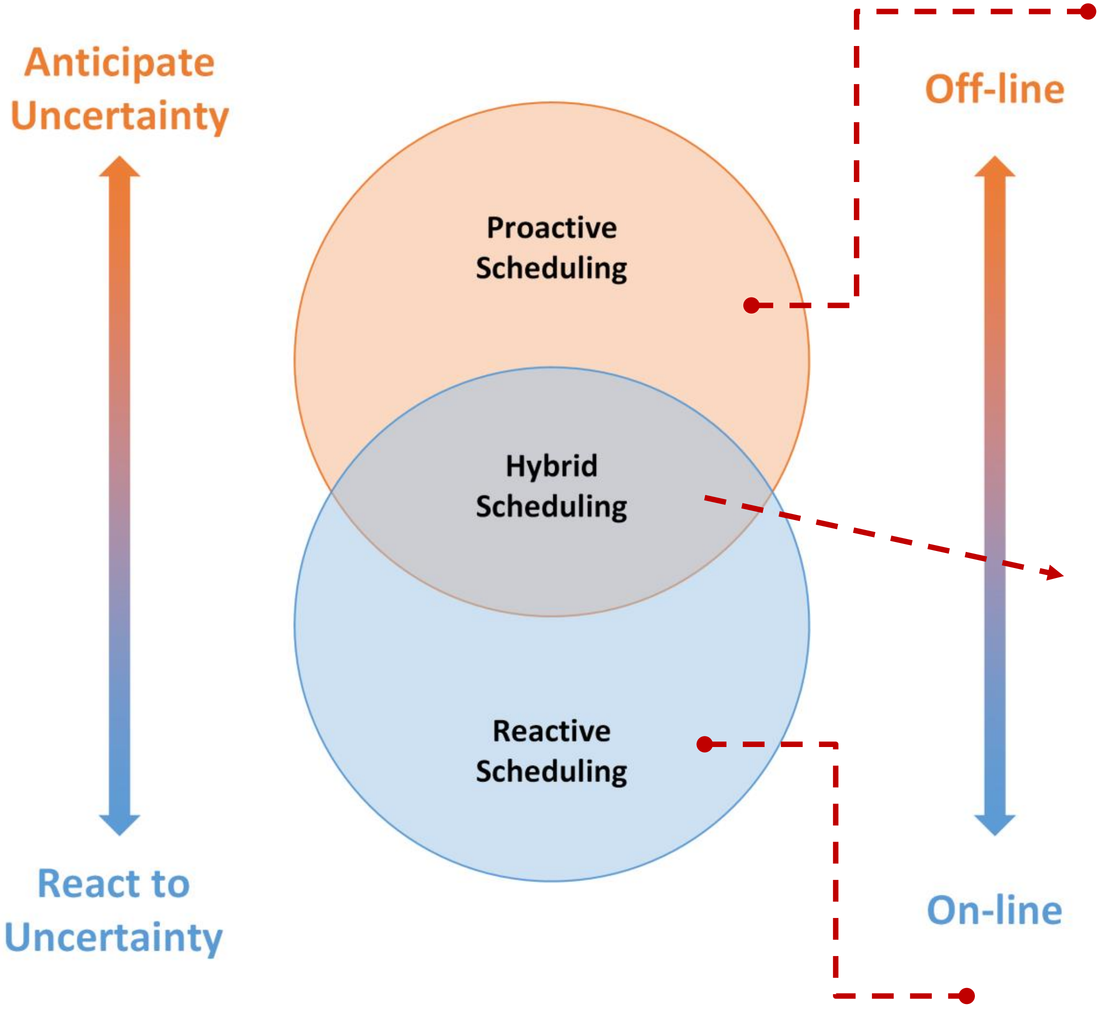
Several production steps, each of which needs multiple resources and needs to fulfil critical production constraints



Unpredicted events, e.g. breakdowns, orders cancellations

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Flat Steel Production Scheduling: State of the Art



Authors	Year	Process Step	Resolution Method	Approach
Lopez et al.	1998	Hot Strip Mill	PCTSP + Metaheuristic (TS)	Deterministic Scheduling
Zhao et al.	2008	Cold Rolling	DTSP + Metaheuristic (DDE) + Heuristic (LS)	Deterministic Scheduling
Valls et al.	2009	Continuous Galvanizing Line	Metaheuristic (TS)	Deterministic Scheduling
Tang et al.	2009	Hot Strip Mill	Heuristic (CT) + Metaheuristic (ACO, SS)	Deterministic Scheduling
Hong et al.	2014	Cold Rolling Mill	Robust Optimization + Metaheuristic (PSO)	Dynamic Scheduling (Proactive)
Nastasi et al.	2015	Cold Rolling	Metaheuristic (SPEAII)	Dynamic Scheduling (Proactive)
Mori et al.	2015	Hot Rolling	Artificial Intelligence (BN + DT)	Dynamic Scheduling (Proactive)
Guo et al.	2019	Primary Steel Making + Cold Rolling Mill	MILP+ Metaheuristic (DDE)	Dynamic Scheduling (Reactive)

Multi-Objective MILP + Multi-Agent Systems + Continuous Flow Model

Authors	Year	Process Step	Resolution Method	Approach
Cowling et al.	2004	Continuous Casting + Hot Strip Mill	Artificial Intelligence (MAS)	Dynamic Scheduling (Reactive)
Tang et al	2008	Color-Coating	Heuristic + Metaheuristic (TS)	Dynamic Scheduling (Reactive)
Wang et al.	2011	Cold Rolling	Artificial Intelligence (MAS) + Metaheuristic (ACO)	Dynamic Scheduling (Reactive)
Hou et al.	2012	Primary Steel Making + Hot Strip Mill	Heuristic	Dynamic Scheduling (Reactive)

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

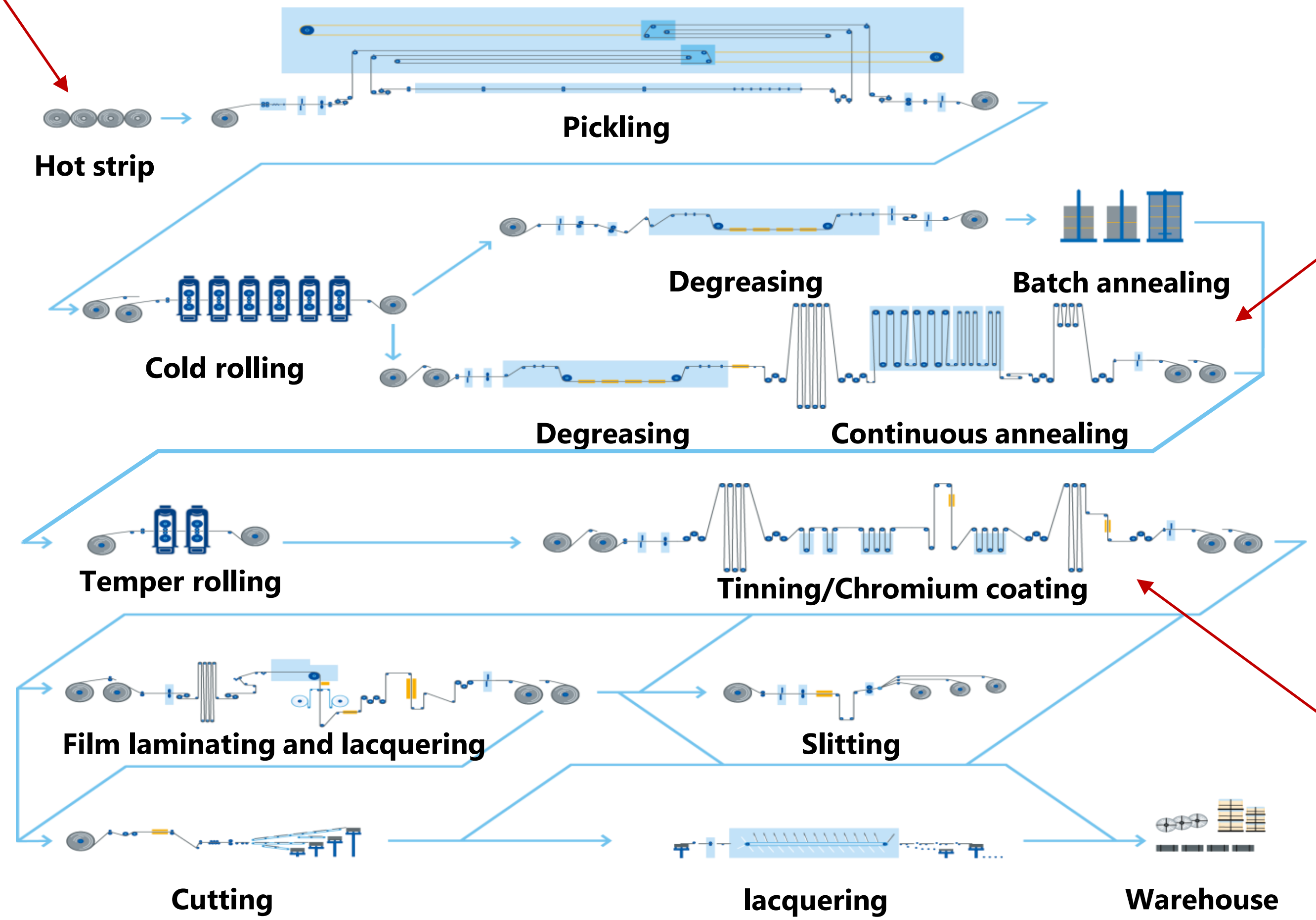
Cold Rolling Process Use Case (thyssenkrupp Rasselstein, Germany)

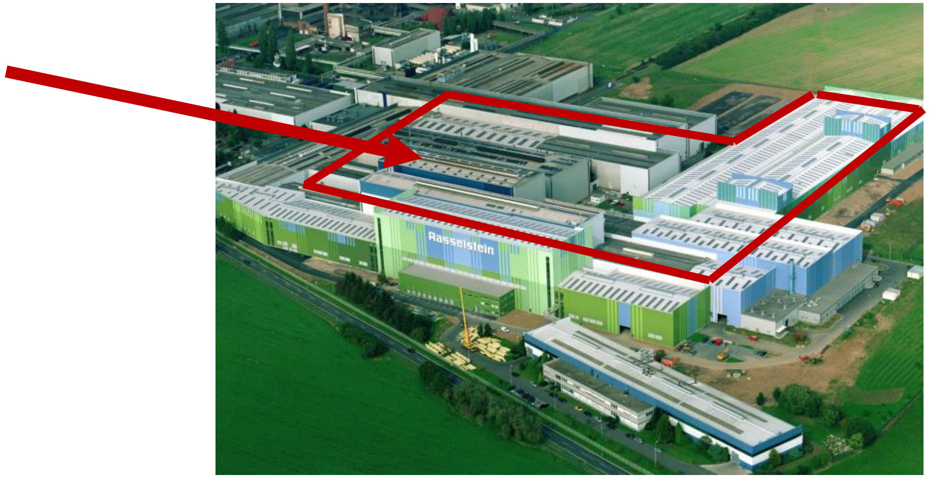
Constraints

Stocks, process-related idle times, routing, order priorities, …

Objective

Maximization of overall plant utilization to meet the monthly planned production volume considering order priorities as well as quality





Disturbances

Machines breakdowns which cause consequent loss of production

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Multi-Objective Mixed-Integer Linear Programming (MOMILP)-Based Approach

Provide a preliminary global optimal resources scheduling under static conditions, i.e. based on production orders and not considering unexpected events

$$\begin{cases} \min f_\omega(x) = c_\omega^T x \\ A_{eq}x = 0, Ax \le 0 \\ x_i^{(L_i)} \le x_i \le x_i^{(U_i)} \; i = 1, \dots, N', x_j \in Z \; for \; some \; j \\ f_k(x) \le f_k^* \quad k = 1, \dots, \omega - 1 \end{cases}$$

MOMILP

where $c_\omega^T x$ is the cost function of a N-component vector argument $x = (x_1, \dots, x_N)$, $A_{eq}x = 0$ are the equality constraints, $Ax \le 0$ are the inequality constraints, $x_i^{(L)}$ and $x_i^{(U)}$ are lower and upper bounds of the i-th component x_i, x_j are integer variables, and f_k^* is the optimal value of the problem with $\omega = k$.

Lexicographic Method

- ✓ Sort objectives according to their importance
- ✓ Solve the problem for objective 1
- ✓ Solve the problem for objective 2 using the best objective 1 found previously as constraint

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Multi-Objective Mixed-Integer Linear Programming (MOMILP)-Based Approach

Iterative Strategy

1° Loop

1. Read input data (e.g. stocks, processing times, due dates, etc.).
2. Group coils into jobs.
3. Select a number of jobs to be processed in a desired time window (jobs are ranked according to their assigned order due date).
4. Solve the MOMILP optimization problem:
   1. Split jobs in a finite set of iterations.
   2. Solve reduced order MOMILP optimization subproblem.
   3. Save optimized plant status and solution.
   4. Go to step ii.
5. Save the final optimized plant status from solution.
6. Go to step 1.

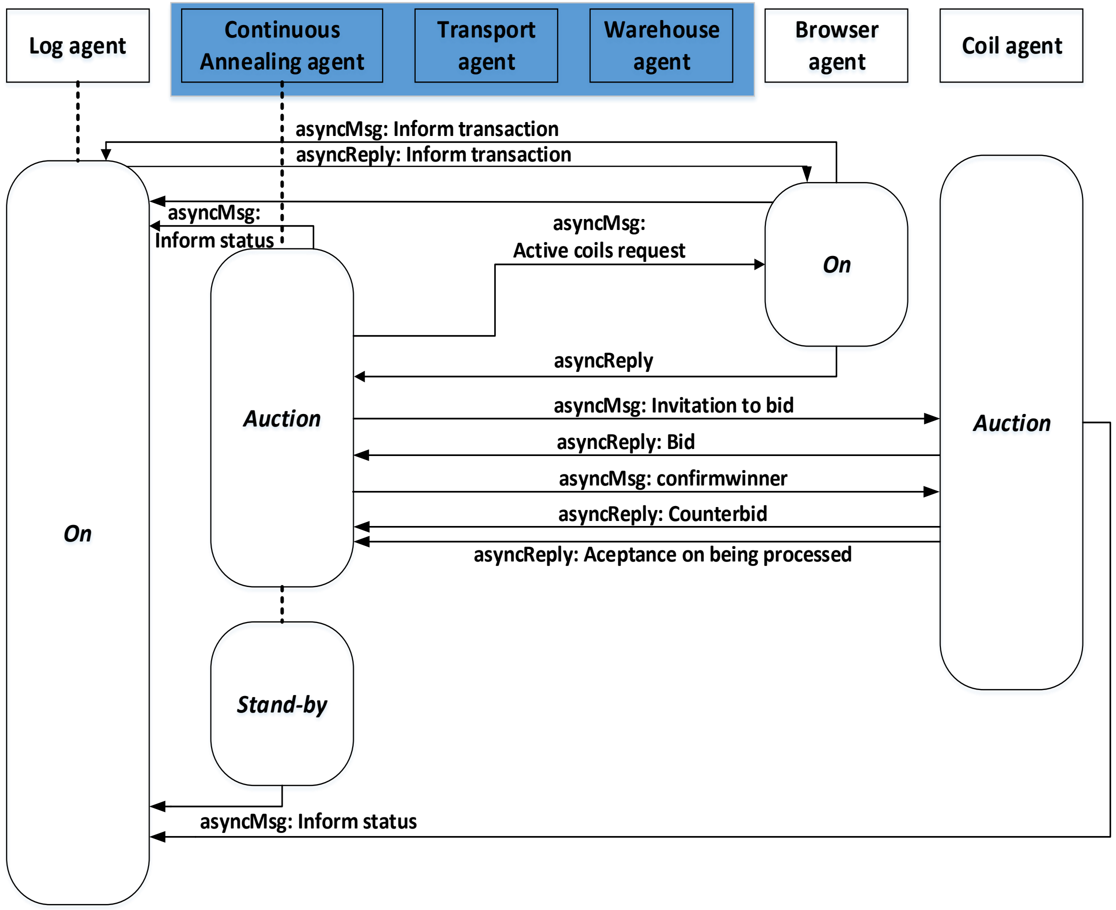
2° Loop

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Auction-Based Multi-Agent System (MAS) Approach

Provide enough feasibility and flexibility when uncertainty regarding resource availability is relevant

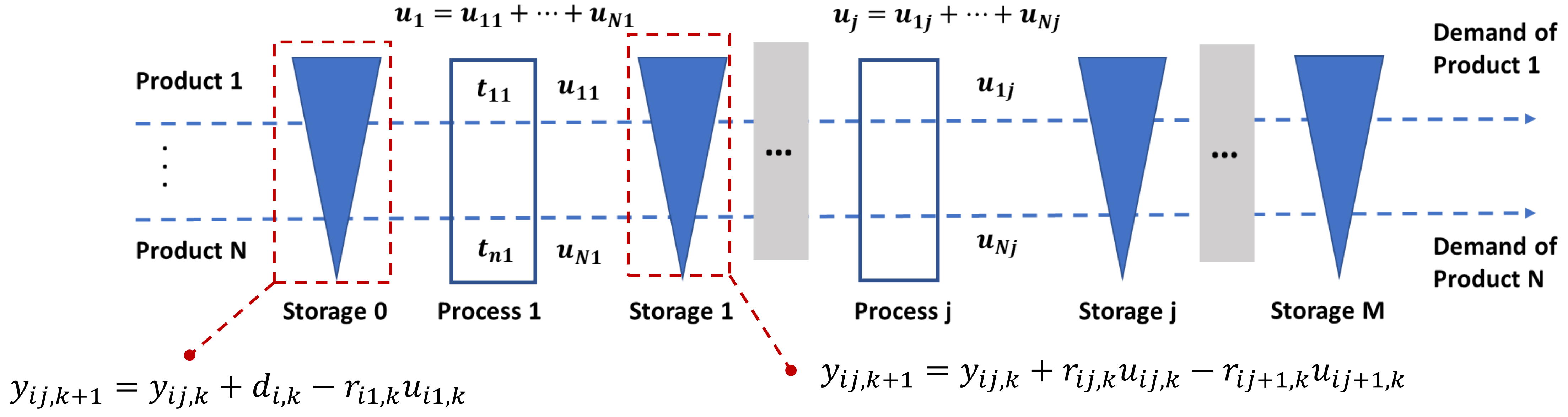
- Negotiation platform uses the Extensible Messaging and Presence Protocol (XMPP) protocol where different agents are involved.
- Multi-optimization objectives are allowed, where an equilibrium between benefits for plants and for coils need to be find incrementally.
- Coils can bid to the different auction processes at the different resources, according to their status.
- The bidding process includes intelligence and is sensitive to the urgency depending on the deadline and the number of failed auctions already experienced, using a rule-based approach.
- Plant agent is in charge of recruiting transport and warehouse resources for the operation before launching the auction itself (pre-auction phase), according to inner logistic rules.



Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Decomposition Approach Based on Continuous Flow Model (CFM)

Provide a long-term production scheduling



- where $y_{ij,k}$ is the amount of product i stored in the storage j at the time step k and $r_{ij,k}$ is the processing rate of product i on machines j and $u_{ij,k}$ is the proportion of product i in the total production on machines j, $d_{i,k}$ is the demand rate of product i at time step k.
- for the upper and lower limit of production on the machine j applies: $0 \leq \sum_i u_{ij,k} \leq \bar{u}_{j,k}$ and $u_{ij,k} \geq 0$ and for the storage the following limits apply $\underline{y}_{j,k} \leq \sum_i y_{ij,k} \leq \bar{y}_{j,k}$.

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Decomposition Approach Based on Continuous Flow Model (CFM)

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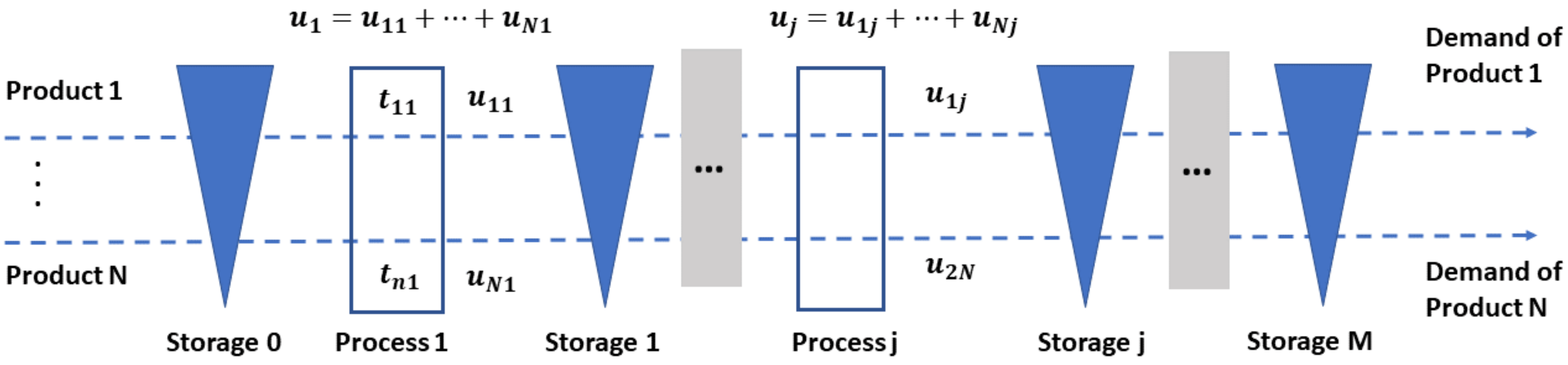


$$\min_{u_{ij,k}} \sum_{k=0}^{n} J_{demand}\left(u_{ij,k}\right) + J_{maschine,cost}\left(u_{ij,k}\right) + J_{use}\left(u_{ij,k}\right) + J_{store}\left(u_{ij,k}\right) + J_{change}\left(u_{ij,k}\right)$$

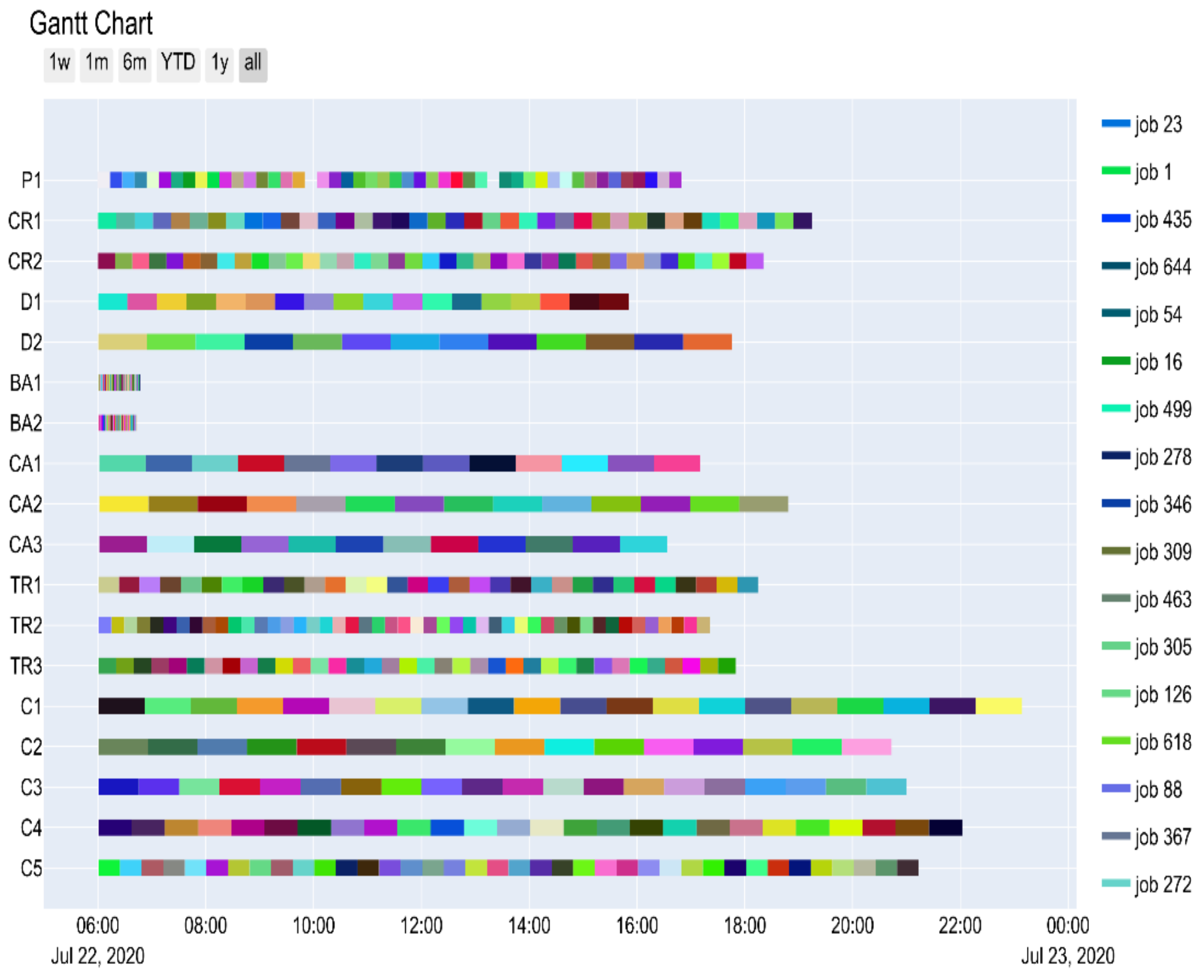
where:

- ❑ $J_{demand}\left(u_{ij,k}\right) = \sum_{i=1}^{N} c_{demand,i} \left\| d_{i,k} - u_{ij,k} \right\|_2$
- ❑ $J_{machine,cost}\left(u_{ij,k}\right) = \sum_{i,j} c_{machine,ij,k} u_{ij,k}$
- ❑ $J_{use}\left(u_{ij,k}\right) = \sum_{i,j} c_{use,ij,k} \left| u_{ij,k} \right|$
- ❑ $J_{store}\left(u_{ij,k}\right) = \sum_j c_{ij,+} + \max\left(\sum_i^N y_{ij,k} - \bar{y}_{j,k}, 0\right) + c_{ij,-} \max\left(\underline{y}_{j,k} - \sum_i y_{ij,k}\right)$
- ❑ $J_{change}\left(u_{ij,k}\right) = \sum_{i,j} c_{ij,k} \left| u_{ij,k} - u_{ij,k-1} \right|$

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

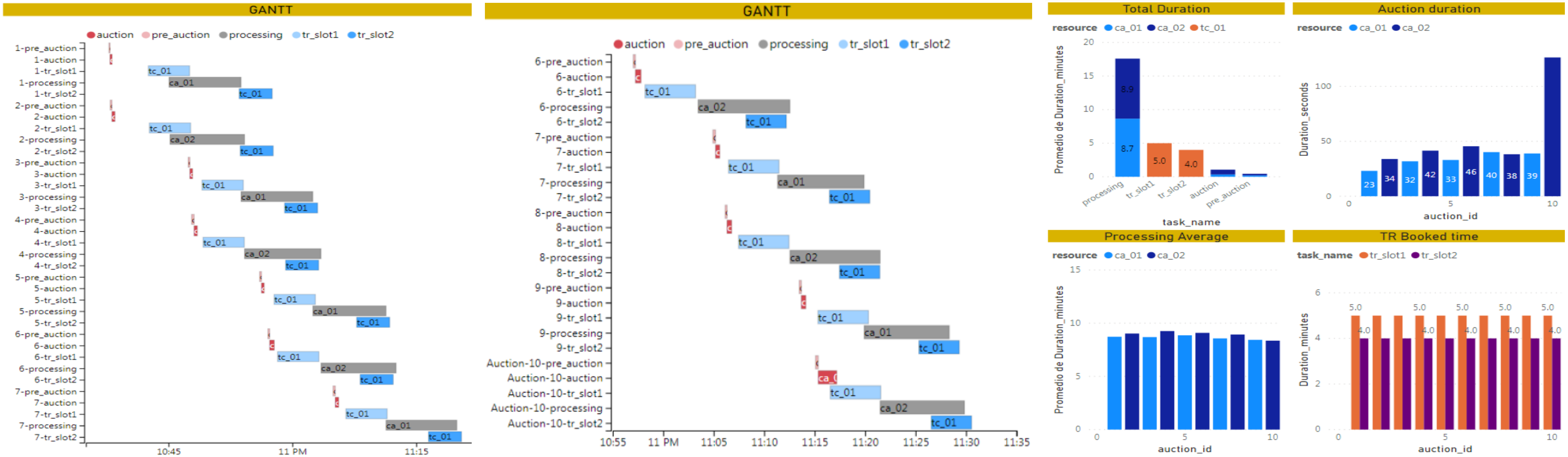
MOMILP Simulation Results

- Global scheduling of 705 jobs in a timeframe of 18h.
- 141 jobs are selected at each iteration (5 iterations totally), each of which composed of 3 coils.
- Jobs are selected according to their due date and are equally distributed among the production stages.
- Average machines processing times are considered.
- Problem solved through GUROBI solver within PuLP library of Python.
- Solver time: 5 minutes for each problem.
- 120 jobs completed at the Tinning/Chromium Coating stage at the end of the simulation (improvement of about 33% and 25%, respectively, on the daily production volume rate and completion time observed in the real use case respectively).
- Average gap of 7.5% from the best bound for the first problem and of 35.2% of average gap from the best bound for the second problem.



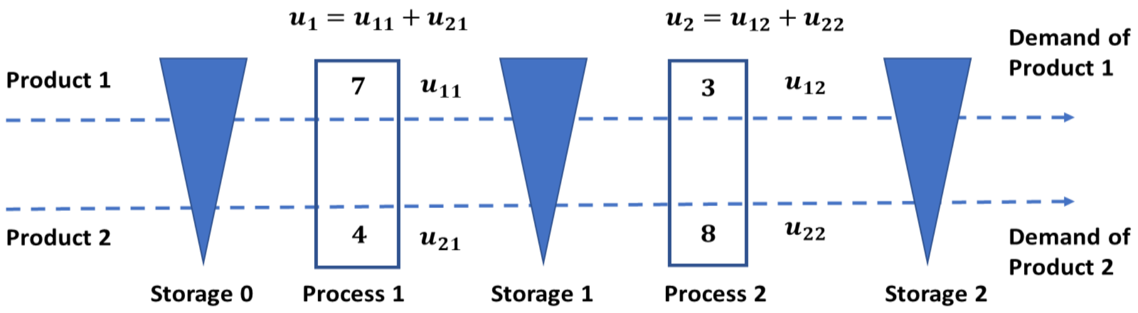
Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

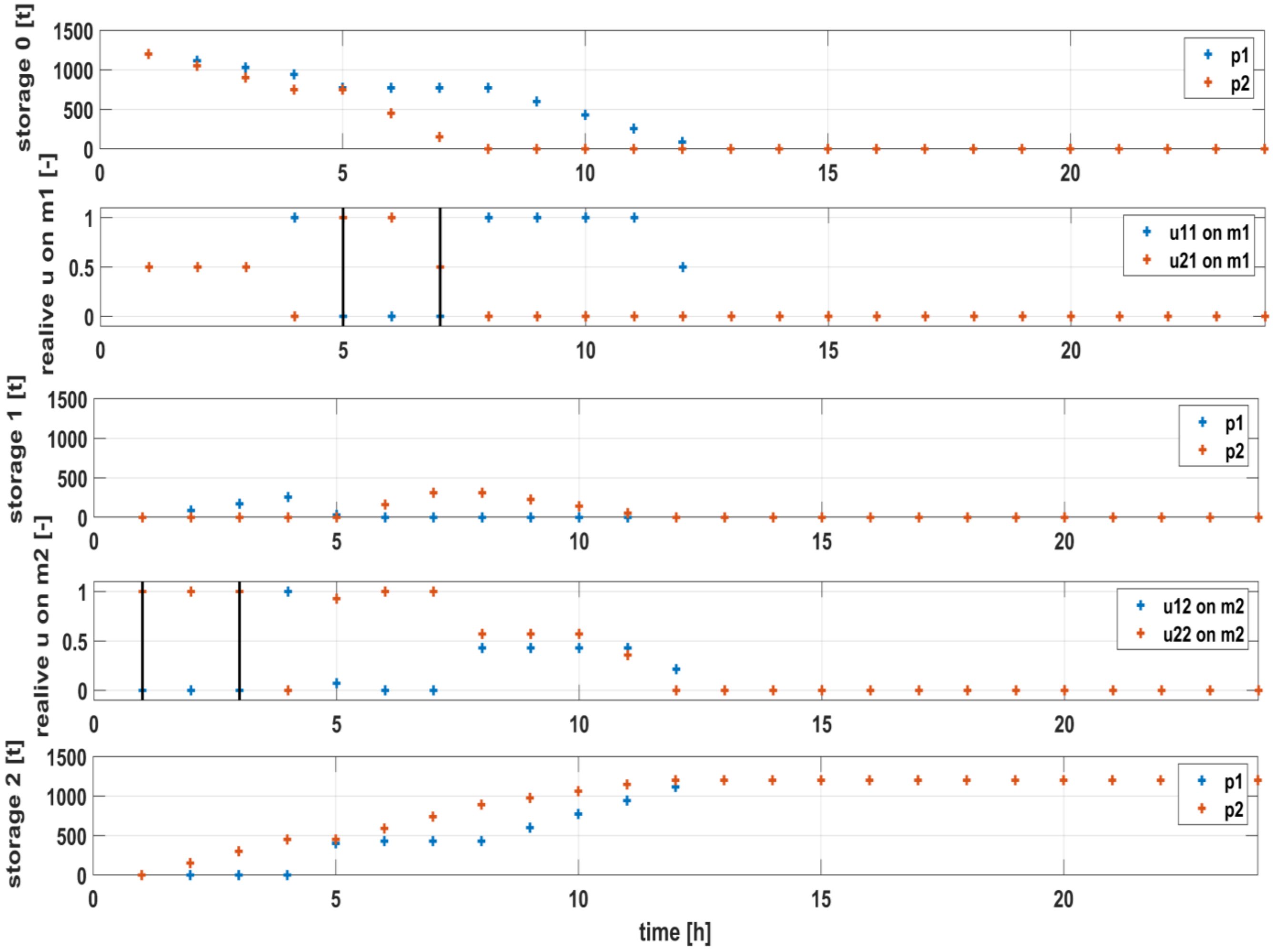
MAS Simulation Results



- Scenario: 2 Continuous Annealing Agents (ca_01, ca_02), 1 Transport Agent (tc_01), 4 Warehouse Agents (wh_01 – wh_04), 10 Coil Agents (coil_001 – coil_010), Browser Agent and Log Agent.
- The approach provides the best solution depending on status and availability of individual resources by considering local demand and specific conditions and constraints imposed by the process and the inner logistics.
- Scheduling is carried out in real time, the system is intrinsically flexible to any issue happening either at plant level or coil level due to quality losses, where relocation of coils inside orders is handled smoothly, avoiding the full rescheduling.

CFM Simulation Results





- Two steps process in which two different products, Product 1 and Product 2, have to be manufactured.
- It is assumed that each product weights 20 tons per item.
- The aim is to produce 1200 tons, i.e., 60 items per product as quickly as possible.

Hybrid Approach for Dynamic Scheduling in Flat Steel Production Processes

Summary of Methods Characteristics

		MOMILP	MAS	CFM
Scope/Granularity		Orders	Coils	Material Flow
Modelling Precision	Modelled Aspects	5	5	1
	Considered Constraints	4	5	3
Reliability	Solution Quality	4	5	4
	Solvability	5	4	5
Forecasting Ability		4	2	5
Efficiency	Computing Time	3	4	4
	Resourced Used	5	4	5
Usability	Acceptance	4	2	5
	Interpretability	3	2	5
Maintainability	Number of Parameters	3	3	5
Transferability	Setup time	4	3	5
	Application Requirements	3	5	4

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