Data Analytics and Optimization in Steel Industry

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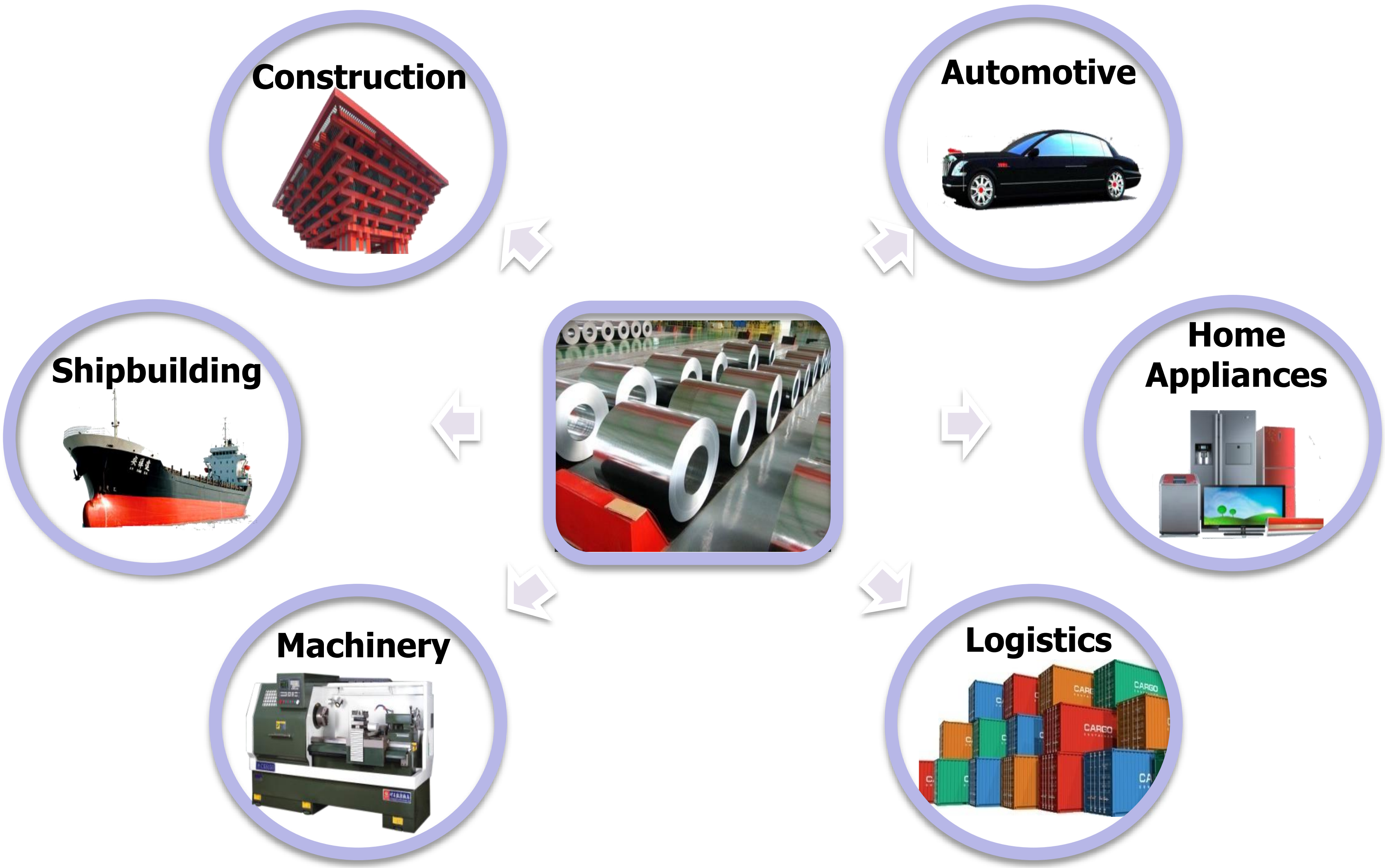
http://schedulingseminar.com

Outline

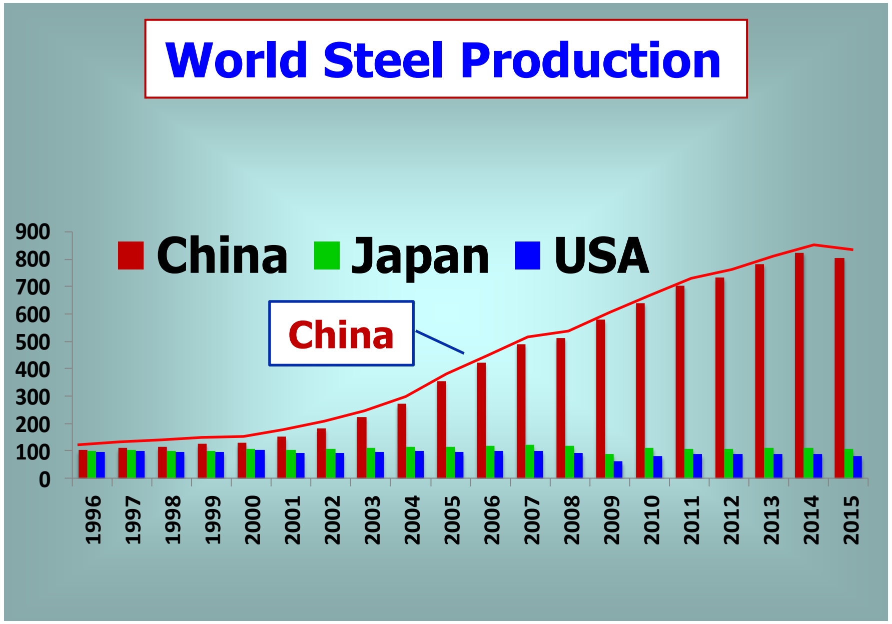
- **Research Background**
- System Modeling and Optimization Method
- Production Scheduling
- Logistics Scheduling
- Energy Optimization
- Data Analytics

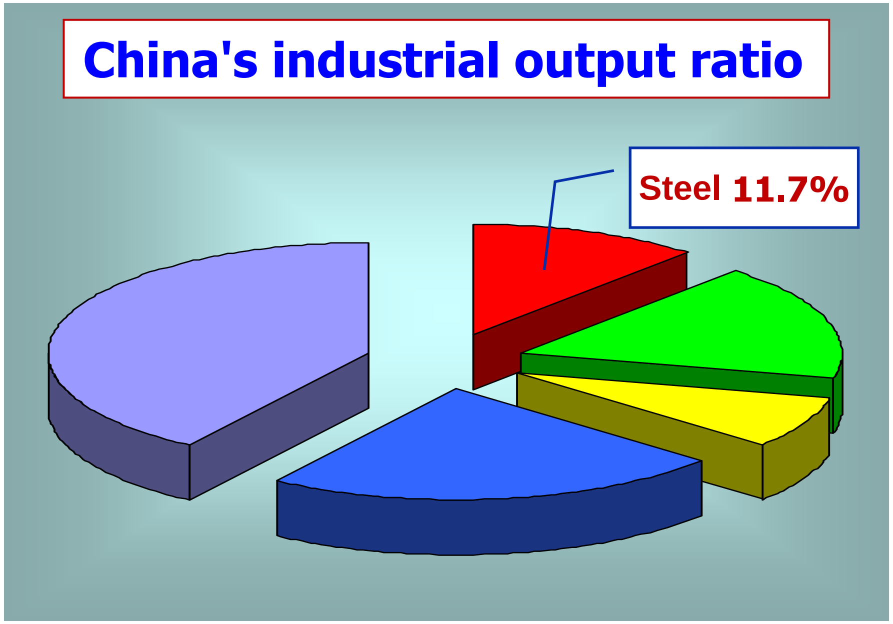
1. Research Background —— Steel is a Key Driver of the World's Economy



1. Research Background —— China is the Largest Steel Producer

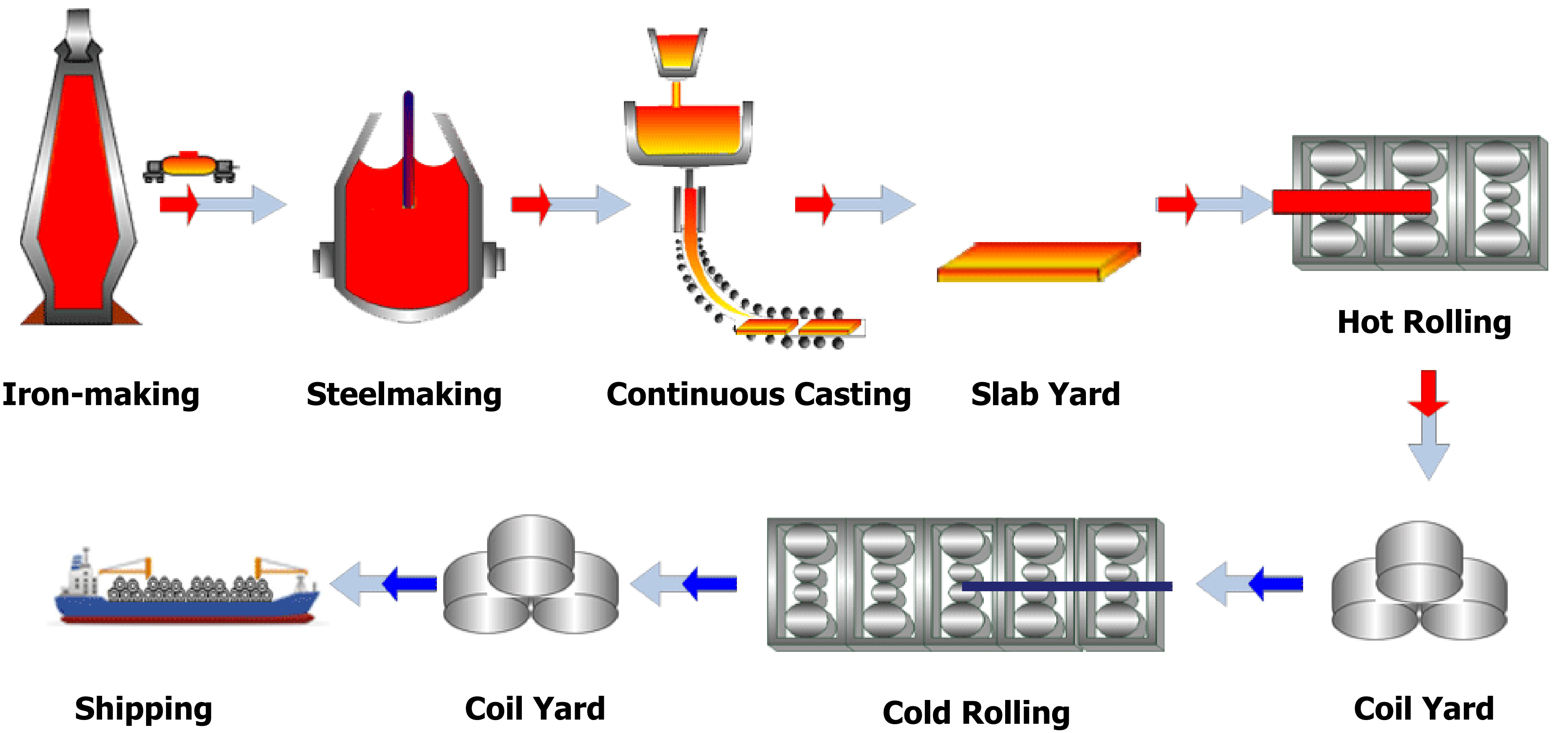
- China has been the largest steel producer in the world for the last twenty consecutive years
- In 2020, China's steel output has reached 1.05 billion tons, accounting for 56.5 percent of the world's steel output
- Steel industry has been one of the pillar industries in China’s national economy



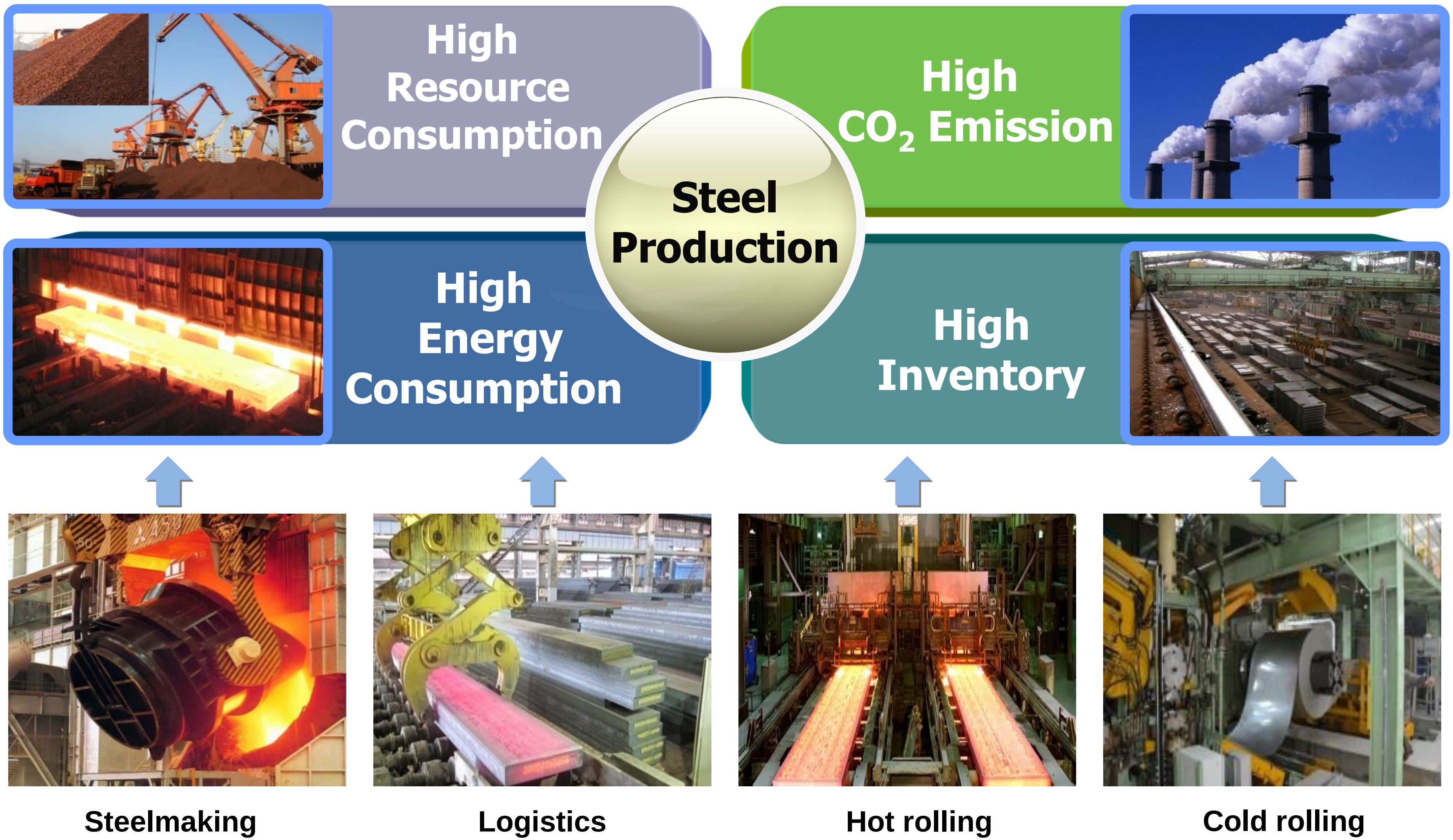


1. Research Background —— Steel Production Process

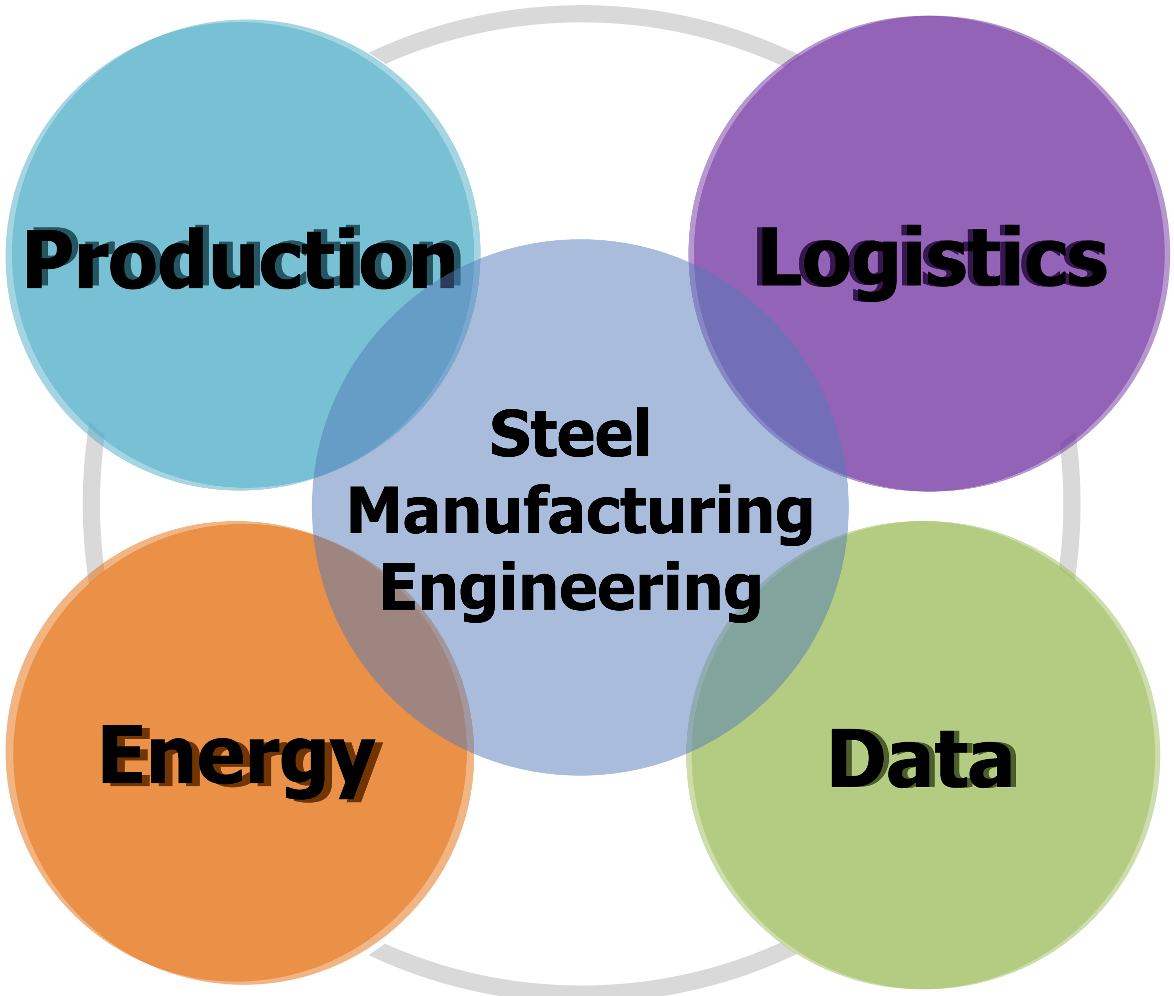
Features: continuous and discrete production, huge devices, high-temperature operations, massive consumption of energy and resource.



1. Research Background —— Challenges Faced by Steel Industry



1. Research Background —— Analytics and Optimization in Steel Industry



Outline

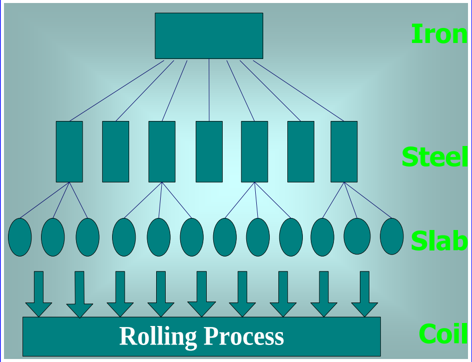
- Research Background
- **System Modeling and Optimization Method**
- Production Scheduling
- Logistics Scheduling
- Energy Optimization
- Data Analytics

2. System Modeling and Optimization Method

New Characteristics

- **Complex physical and chemical processes**
- **Large variety and low volume products**
- **Complicated logistics structure**

Complicated Production Process



Large Variety and Low Volume

Huge Chemical Equipment

Complicated Logistics Structure

2. System Modeling and Optimization Method — System Modeling

Product Quality → **Various Demands** ← Customer Demand

- Physical performance
- Chemical performance
- Mechanical performance

Engineering Object

Time Management

Production | Logistics | Energy | Equipment

Steelmaking

Hot rolling

Cold rolling

Logistics

Space Management

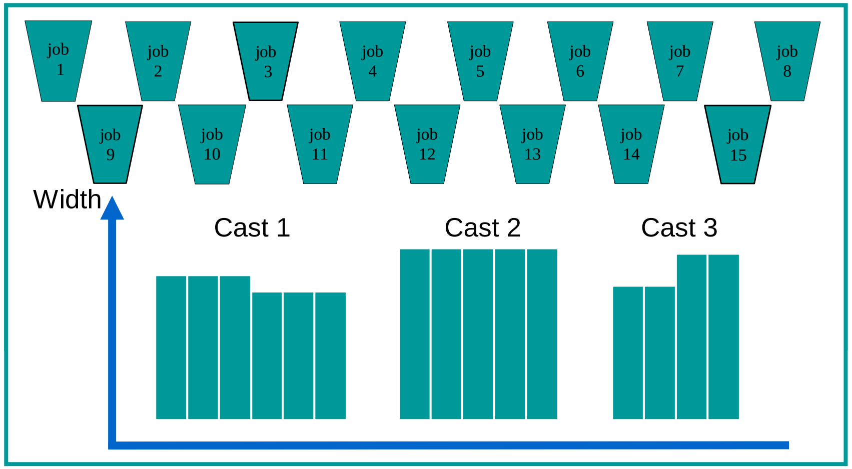
Time Scheduling → **Various Products** ← Space Scheduling

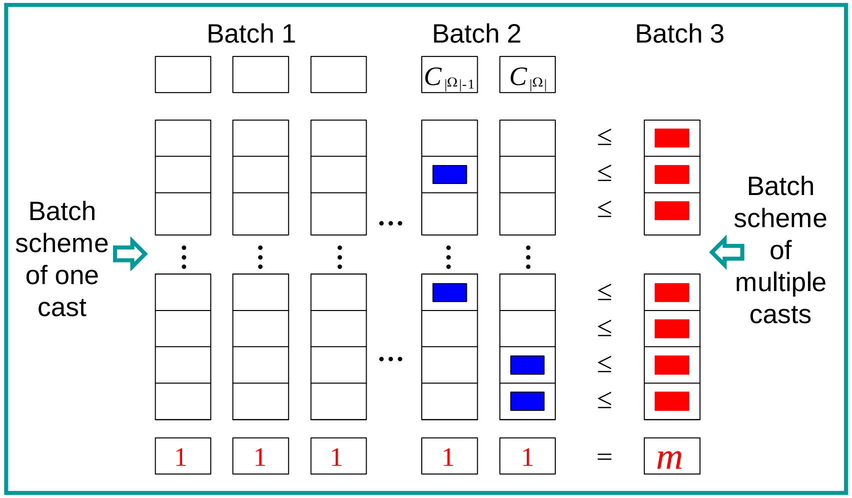
- raw materials
- semi-finished products
- finished products

2. System Modeling and Optimization Method — System Modeling

Set-Packing modeling

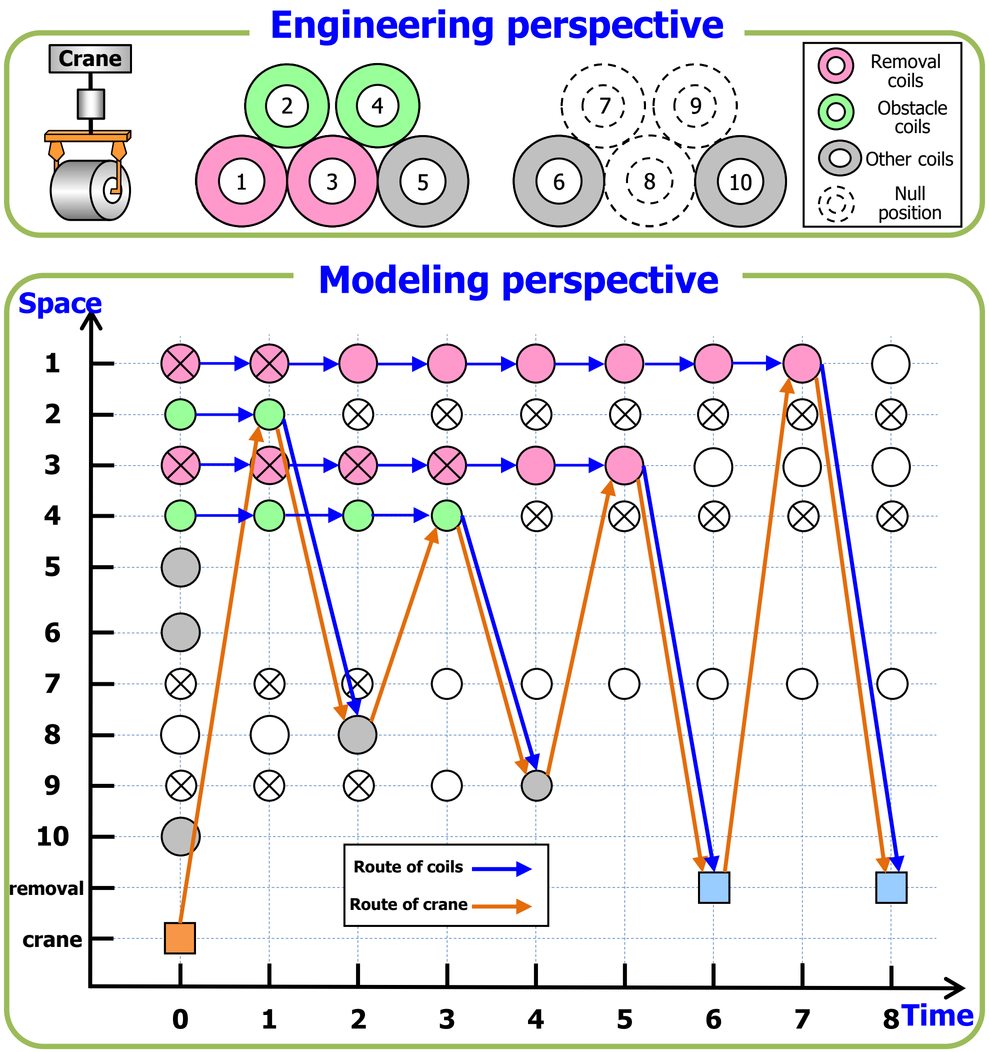
- The problem is transformed into the optimization combination of multiple batch schemes of jobs, and the Set-Packing model is formulated;
- A batch scheme of jobs is defined as an element that includes the combination of jobs;
- The sub-problems are to describes the generation rules of batch schemes of jobs;
- Effectively reduce the number of variables and constraints and improve the solving efficiency of the model.





Space-time network flow modeling

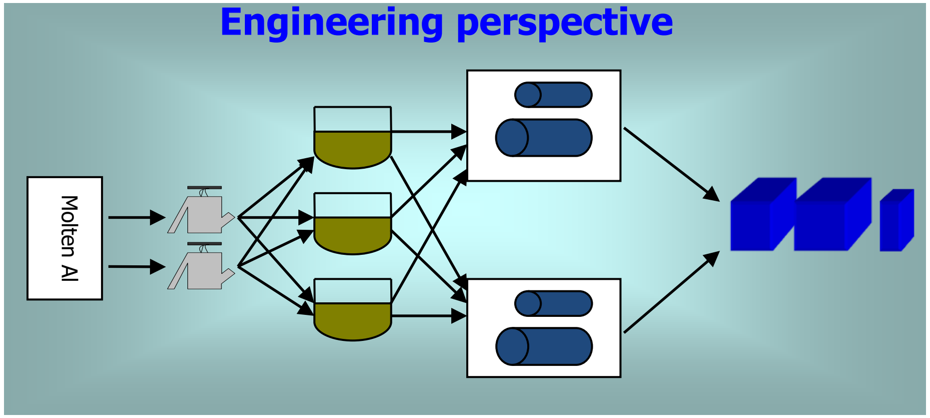
- The space-time is discretized into grid and depicted based on network graph. Each node represents a location, each edge indicates a crane's move between two locations in a stage;
- The spatial location includes all the locations in the storage area and the entry, exit and initial location of the crane;
- The scheduling of task sequence is transformed into the allocation of crane movement in stages, and an event-based space-time network model is established.

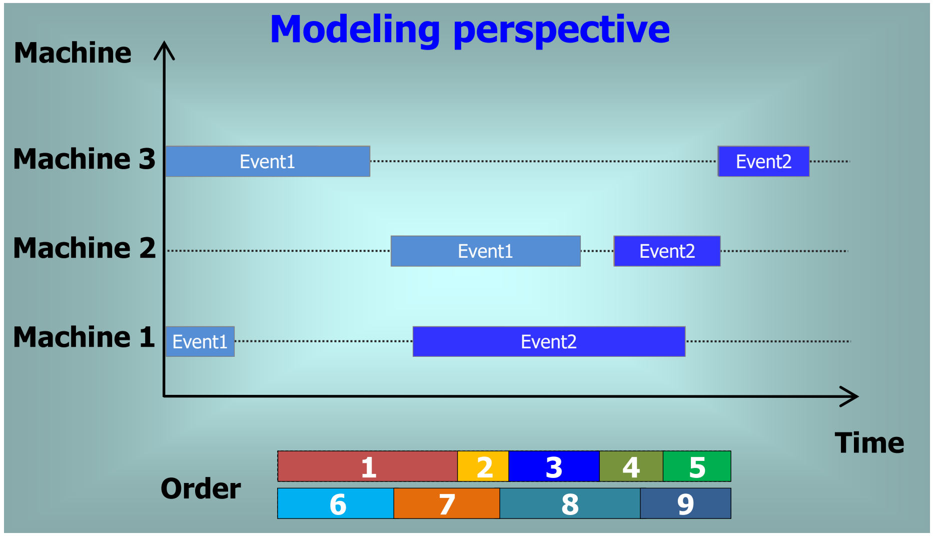


Y. Yuan and L. Tang. Novel time-space network flow formulation and approximate dynamic programming approach for the crane scheduling in a coil warehouse. *European Journal of Operational Research*, 2017, 262(2): 424-437.

Continuous-time based modeling

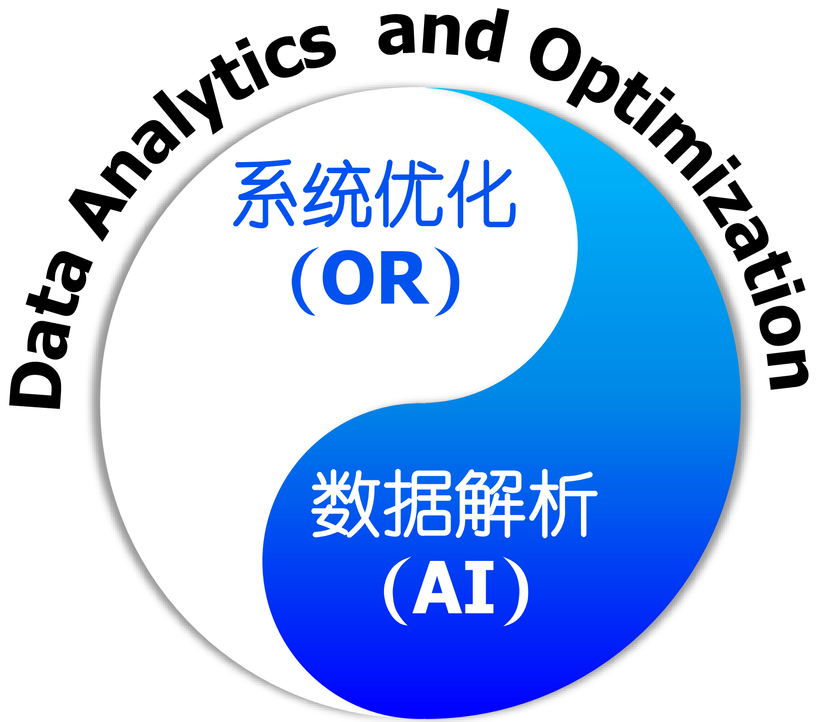
- Continuous-time modeling allows tasks take place at any point in the continuous domain of time, and thus improve the accuracy and efficiency of modeling;
- Unit-specific event-based approach is used for network-represented process, which allows batches to merge/split.
- This model needs fewer event points describing beginning and end of events and has better computational performance.





Q. Guo, L. Tang, J. Liu, S. Zhao. Continuous-time formulation and differential evolution algorithm for an integrated batching and scheduling problem in aluminium industry. ***International Journal of Production Research***, 2020.

2. System Modeling and Optimization Method



Data Analytics and Optimization (DAO)

L. Tang, Y. Meng. Data analytics and optimization for smart industry. ***Frontiers of Engineering Management***, 2021, 8(2): 157-171.

2. System Modeling and Optimization Method — System Modeling

- Mathematical modeling is used to formulate the identifiable and quantifiable parts of the production, logistics and energy scheduling problems. Meanwhile, data analytics supplements to the mathematical model for constructing the parts that are hardly to model and forming the parameters of the model.

Mathematical Modeling

$$\text{Max } Z=\sum_{j\in P}\sum_{i\in O_j}F_iX_{ij}-\sum_{j\in P}\sum_{i\in O_j}\Big(C_{1ij}X_{ij}+\sum_{k\in O_j\cap R_i}C_{2ik}Y_{ikj}\Big)$$

$s.t.$

$$\sum_{j\in Q_i}X_{ij}\le 1 \qquad \text{for } i\in N$$

$$\sum_{i\in O_j}h_iX_{ij}\le H \qquad \text{for } j\in P$$

$$\sum_{k\in O_j}Y_{kkj}=1 \qquad \text{for } j\in P$$

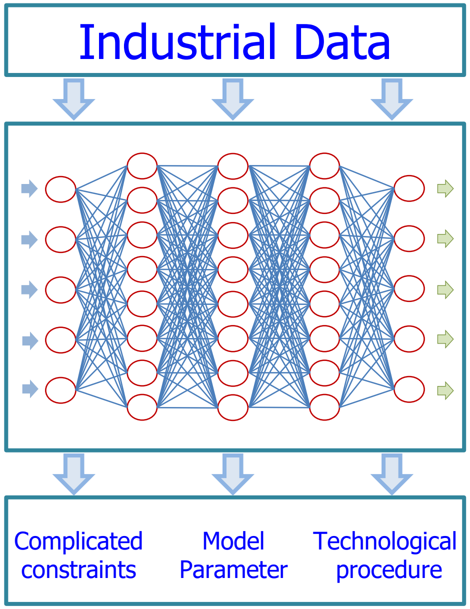
$$Y_{ikj}\le Y_{kkj} \qquad \text{for } j\in P,\ k\in O_j,\ i\in O_j\cap R_k$$

$$X_{ij}=\sum_{k\in O_j\cap R_i}Y_{ikj} \qquad \text{for } j\in P,\ i\in O_j$$

$$X_{ij}\in\{0,1\} \qquad \text{for } j\in P,\ i\in O_j$$

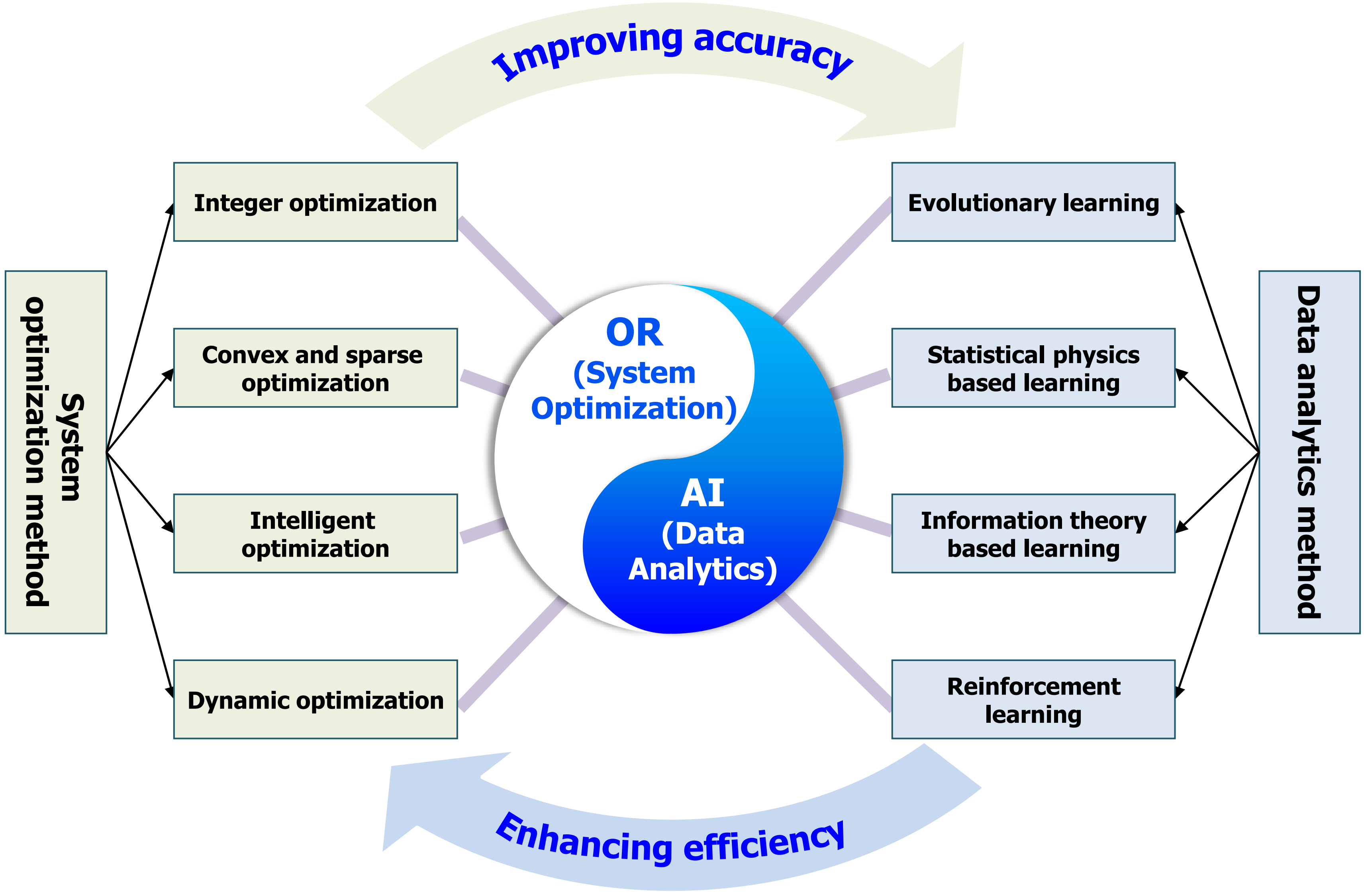
$$Y_{ikj}\in\{0,1\} \qquad \text{for } j\in P,\ k\in O_j,\ i\in O_j\cap R_k$$

Data Analytics



L. Tang, Y. Meng. Data analytics and optimization for smart industry. ***Frontiers of Engineering Management***, 2021, 8(2): 157-171.

2. System Modeling and Optimization Method



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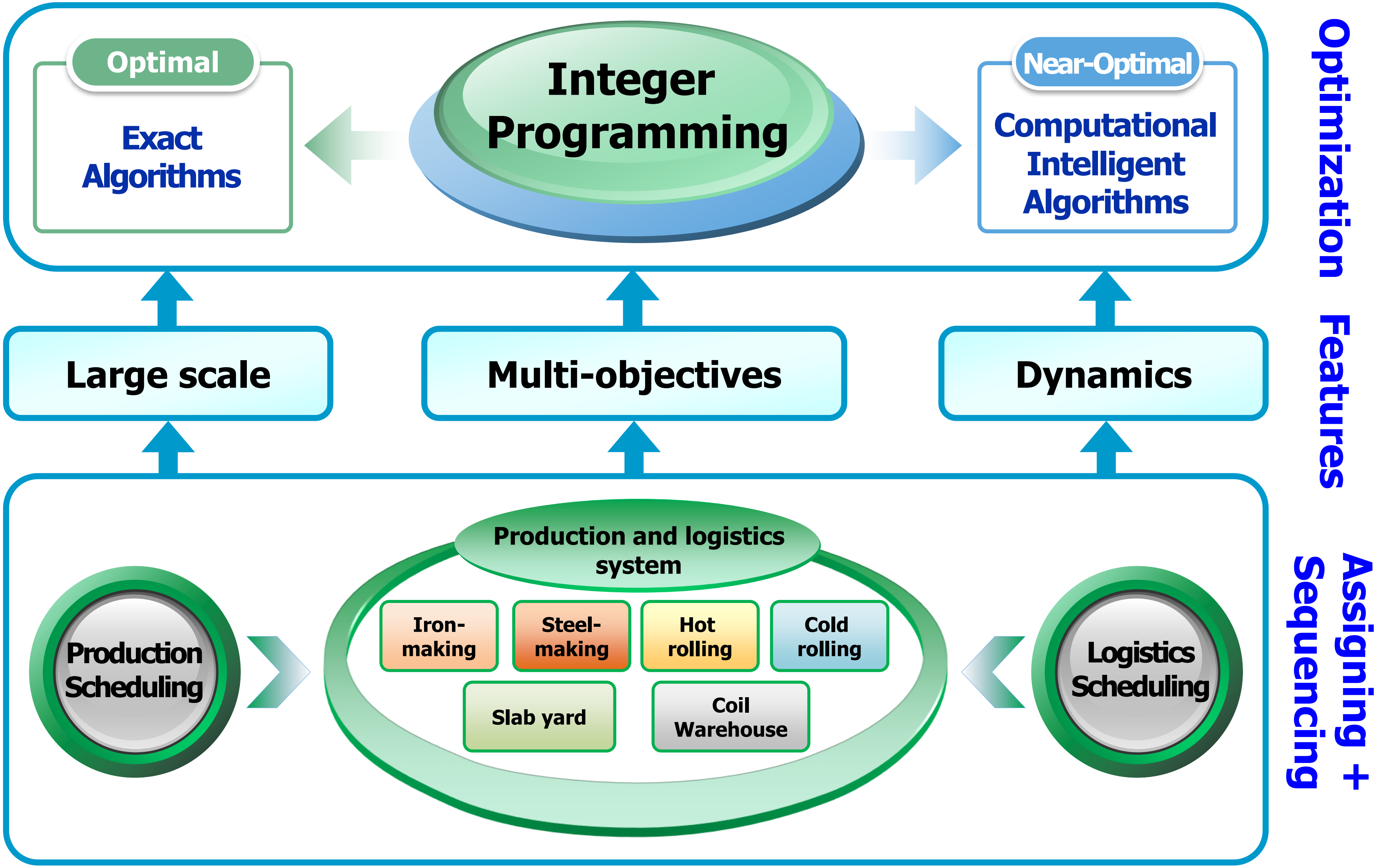
2. System Modeling and Optimization Method



2. System Modeling and Optimization Method

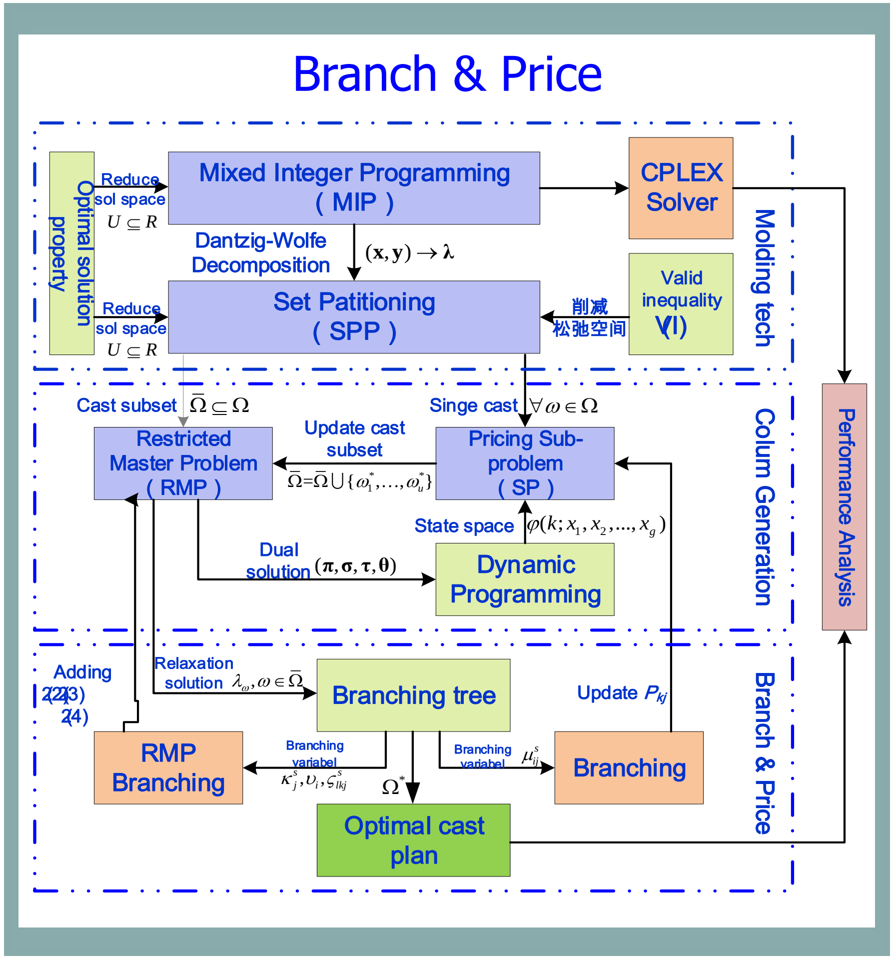
Integer Optimization Methods and Improvement

Algorithm	Branch & Price	LR/Benders Decomposition	(OA) Outer Approximation	Branch & Cut
Problem	Casting problem with width decision in steel-making and continuous casting production	Integrated problem of ship scheduling and storage space allocation	MINLP	Crane scheduling problem in slab warehouse
Theory	Multilayer branching strategy; Low dimension DP	Multiple cuts; Valid inequality; Variable reduction	Multiple linear cuts; Quadratic cuts	Model tightening; Valid inequality; Variable reduction
Effect	Superior to commercial optimization software CPLEX in performance	Superior to traditional Benders in performance	Superior to traditional OA and commercial optimization software in performance	Superior to commercial optimization software CPLEX in performance

- The proposed algorithms are superior to international best commercial solving software in terms of solving time, precision and stability.

Integer Optimization — Brach & Price

- A Branch & Price approach based on set packing model;
- Discover the trapezoidal feature of the cost structure, and construct a new low-dimensional dynamic programming algorithm, which overcomes the high-dimensional feature of the conventional dynamic programming algorithm;
- Propose a multi-layer branching strategy with sub-problem structure;
- For the first time, optimal solving of the same kind of problem is realized.



Integer Optimization — Lagrangian Relaxation

- The coupling/complex constraint is relaxed into the objective function by Lagrangian multiplier, thus decouple and decompose the full problem into several independent sub-problems
  - **Decomposition**： batch decoupling strategy; stage-based decomposition
  - **Dual problem solution**: hybrid backward and forward dynamic programming;

Lagrangian Relaxation Algorithm

$$z_{SC} = \min \sum_{j=1}^{n} c_j x_j$$

$$s.t. \sum_{j=1}^{n} a_{ij} x_j \geq 1, \quad i = 1,2,\cdots,m,$$

$$x_j \in \{0,1\}, \quad j = 1,2,\cdots,n.$$

Multiplier relaxation →

$$z_{LRSC}(\lambda) = \min \sum_{j=1}^{n} c_j x_j + \sum_{i=1}^{m} \lambda_i (1 - \sum_{j=1}^{n} a_{ij} x_j)$$

$$s.t. \quad x_j \in \{0,1\}, j = 1,2,\cdots,n,$$

$$\lambda \geq 0.$$

↓ decomposition

$$z_{LRSC}(\lambda) = \min \sum_{j=1}^{n} d_j x_j + \sum_{i=1}^{m} \lambda_i$$

$$s.t. \quad x_j \in \{0,1\}, j = 1,2,\cdots,n,$$

$$\lambda \geq 0.$$

← solve subproblems optimally

$$z_{LRSC}(\lambda) = \sum_{j=1}^{n} d_j x_j^* + \sum_{i=1}^{m} \lambda_i .$$

$$x_j^* = \begin{cases} 1, & if \ d_j \leq 0 \\ 0, & otherwise \end{cases}$$

Lower bound ↑ (to z_{SC})

L. Tang, H. Xuan, J. Liu. A new Lagrangian relaxation algorithm for hybrid flowshop scheduling to minimize total weighted completion time. ***Computers & Operations Research***, 2006, 33(11): 3344-3359.

2. System Modeling and Optimization Method

Benders Decomposition Algorithm

Various Valid Inequalities

$$\sum_{j\in I\setminus\{i\}} u_{ij} \neq \sum_{j\in I\setminus\{i'\}} u_{i'j} \qquad \sum_{(r,s)\in G_i} y_{irs} \leq 0$$

⇨ Improving lower bound

Combinatorial Benders Cuts

$$\text{MILP\_CB} := \begin{cases} \textbf{A\_MILP}_{\text{LP}} \\ \upsilon(\textbf{A\_MILP}_{\text{LP}}) \leq \text{UB}-\varepsilon \end{cases}$$

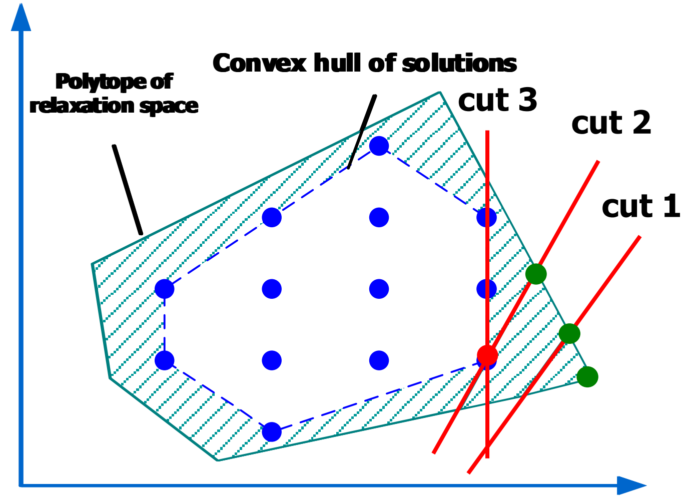
⇨ Accelerating convergence

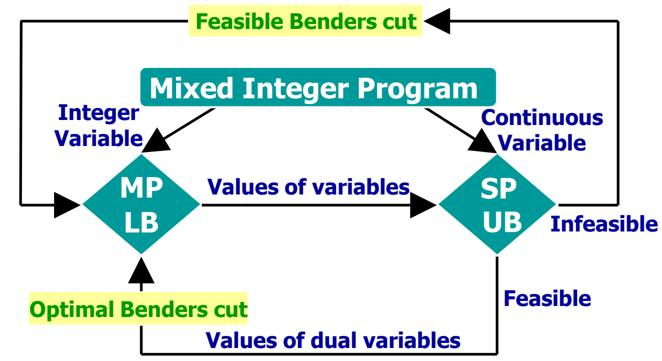
Variable Reduction

$$v[\mathbf{MP}^k(\mathbf{IR})] > UB \quad v[\mathbf{MP}^k{}_{LP}(\mathbf{IR})] > UB$$

⇨ Reducing search space

Structure





L. Tang, D. Sun and J. Liu. Integrated storage space allocation and ship scheduling problem in bulk cargo terminals. ***IISE Transactions***, 2016, 48(5): 428-439. (**Featured Article**)

2. System Modeling and Optimization Method

Outer Approximation(OA) Algorithm

Multi-generation Cuts

$$\alpha \ge f\left(x^k\right)+h^T\cdot y+\left(\lambda^k\right)^T\cdot\left(g\left(x^k\right)+H\cdot y\right) +\left(\mu^k\right)^T\cdot\left(A\cdot x^k+E\cdot y-b\right) \qquad k\in KFS$$

$$\left(\lambda^k\right)^T\cdot\left(g\left(x^k\right)+H\cdot y\right)+\left(\mu^k\right)^T\cdot\left(A\cdot x^k+E\cdot y-b\right)\le 0 \qquad k\in KIS$$

⇨ Accelerating convergence

Partial Surrogate Cuts

$$\left(\lambda^k\right)^T\cdot\left[Hy+Dw+g(v^k)\right]-\left(\mu^k\right)^T A_2\left(v-v^k\right)\le 0$$

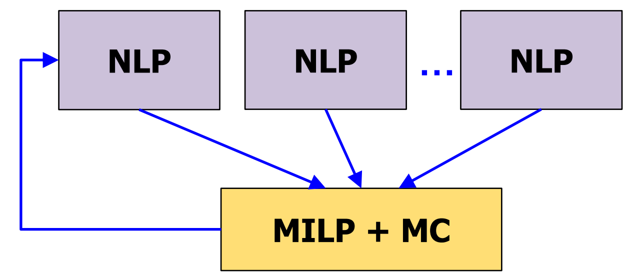
⇨ Tightening lower bound

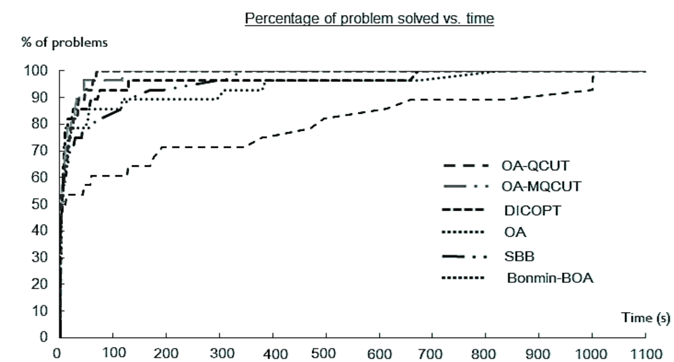
Hybrid Strategy of OA and GBD

Scaled Quadratic Cuts with Multi-generation Cuts

⇨ Improving efficiency

Structure



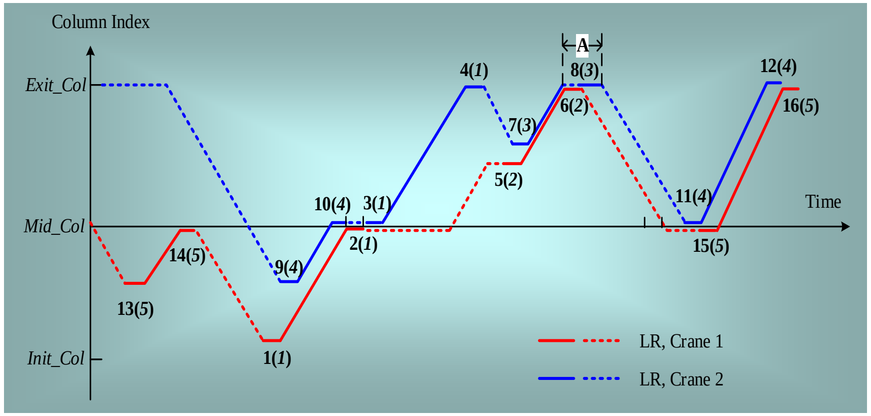


L. Su, L. Tang and I.E. Grossmann. Computational strategies for improved MINLP algorithms. ***Computers & Chemical Engineering***, 2015, 75: 40-48.

2. System Modeling and Optimization Method

Integer Optimization — Branch & Cut

- Branch & Cut developed；
- The model tightening technique is proposed based on the reformulation with compact lower bound；
- A serial of valid inequalities (e.g. subtour elimination) to accelerate the convergence of the algorithm;
- Variable reduction;
- The algorithm can solve the real scale problems to optimal, and is superior to CPLEX in performance.



Instance	CPLEX sol	CPLEX time (s)	CPLEX Gap (%)	B&C sol	B&C time (s)	B&C number of cuts
1	47	5.273	0	47	2.902	4
2	82	123.225	0	82	73.586	10
3	92	232.270	0	92	55.427	8
18	432	85.099	0	432	73.554	4
19	460	248.010	0	460	81.979	26
20	73	3.978	0	73	3.728	12
Avg		142.119	0		70.180	30

X. Cheng, L. Tang and P.M. Pardalos. A Branch-and-Cut algorithm for factory crane scheduling problem. ***Journal of Global Optimization***, 2015, 63(4): 729-755.

2. System Modeling and Optimization Method

Computational Intelligent Optimization

Population based Algorithm

- Independent of prior knowledge
- Crossover, mutation operators
- Generate new individuals by crossover & mutation operators

Differential evolution, particle swarm

Neighborhood based Algorithm

- Dependent of prior knowledge
- Neighborhood construction
- Generate new solution by neighborhood

Tabu search, local search, annealing

2. System Modeling and Optimization Method

Differential Evolution with An Individual–Dependent Mechanism

Individual–Dependent Parameters Setting

$$F_i = randn(\frac{i}{NP}, 0.1) \quad CR_i = randn(\frac{i}{NP}, 0.1)$$

→ Self-adaptive allocation

Individual–Dependent Mutation Operator

$$DI = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left\|\mathbf{x}_i - \frac{1}{N}\sum_{j=1}^{N}\mathbf{x}_j\right\|^2} \quad DF = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(f(\mathbf{x}_i) - \frac{1}{N}\sum_{j=1}^{N}f(\mathbf{x}_j)\right)^2}$$

→ Self-adaptive selection

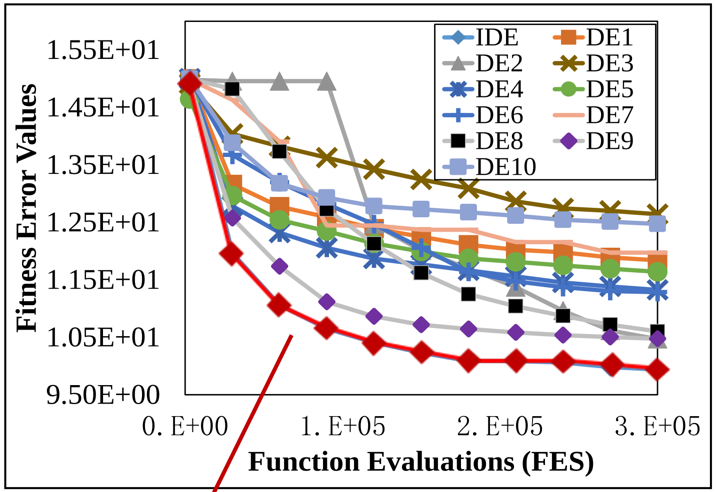
Perturbations with Small Probability

$$d = L + rand(0,1) * (U - L)$$

→ Global search

Performance

Algorithms	Dimension of Benchmark Functions								
	10-D			30-D			50-D		
	-	=	+	-	=	+	-	=	+



The experiment demonstrates the algorithm's outstanding performance

L. Tang, Y. Dong and J.Y. Liu. Differential evolution with an individual–dependent mechanism. ***IEEE Transactions on Evolutionary Computation***, 2015, 19(4): 560-574. (**ESI Highly Cited Paper**)

2. System Modeling and Optimization Method

Improved Differential Evolution Algorithm for Dynamic Scheduling

Incremental Mechanism for Initial Population Generation ⇒ Improving efficiency

Real-coded Matrix Representation ⇒ Avoiding invalid solutions

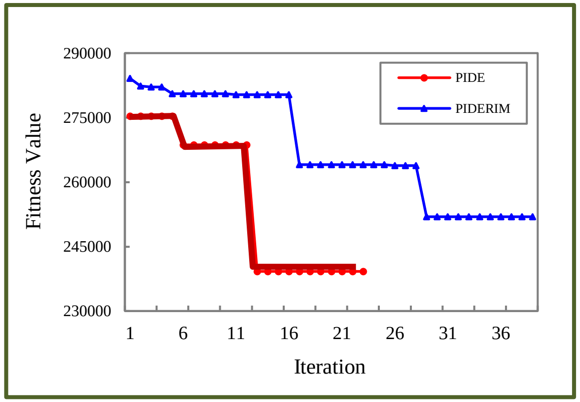
$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1S} \\ a_{21} & a_{22} & \cdots & a_{2S} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NS} \end{pmatrix}$$

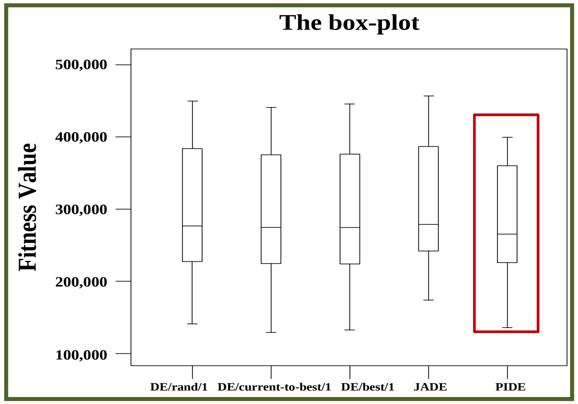
Randomly Mutation Operator ⇒ Expanding search space

$$\mathbf{v}_{i,g} = \mathbf{x}_{i,g} + F(\mathbf{x}_{r1,g} - \mathbf{x}_{r2,g})$$

$$+F(\mathbf{x}^M_{best,g} - \mathbf{x}_{i,g}) + F(\mathbf{x}_{r3,g} - \mathbf{x}_{r4,g}) + F(\mathbf{x}^M_{r5,g} - \mathbf{x}^M_{r6,g})$$

Performance





Algorithm has a fast convergence speed

L. Tang, Y. Zhao and J.Y. Liu. An improved differential evolution algorithm for practical dynamic scheduling in steelmaking-continuous casting production. ***IEEE Transactions on Evolutionary Computation***, 2014, 18(2): 209-225. (**ESI** Highly Cited Paper)

2. System Modeling and Optimization Method

Hybrid Multi-objective Evolutionary Algorithm

Incorporating the Concepts of Personal Best and Global Best ⇨ Avoiding local optimum

Multiple Crossover Operators to Update the Population ⇨ Increasing robustness

Propagating Mechanism ⇨ Improving diversity

Performance

Problems	*HMOEA* $\tilde{x}_{IQR}$	*AbYSS* $\tilde{x}_{IQR}$	*SMPSO* $\tilde{x}_{IQR}$	*NSGA-II* $\tilde{x}_{IQR}$	*SPEA2* $\tilde{x}_{IQR}$	
ZDT1	1.572e-04 $_{4.0e-05}$	1.852e-04 $_{4.0e-05}$	1.170e-04 $_{3.5e-05}$	2.203e-04 $_{4.6e-05}$	2.198e-04 $_{2.9e-05}$	+
ZDT2	7.568e-05 $_{1.4e-05}$	1.022e-04 $_{5.4e-05}$	5.012e-05 $_{4.3e-06}$	1.598e-04 $_{4.5e-05}$	1.783e-04 $_{4.5e-05}$	+
ZDT3	7.012e-05 $_{1.2e-05}$	1.670e-04 $_{2.3e-05}$	7.555e-05 $_{2.9e-05}$	1.852e-04 $_{2.2e-05}$	1.114e-04 $_{2.3e-05}$	+
ZDT4	1.502e-04 $_{4.5e-05}$	4.599e-04 $_{3.6e-04}$	1.507e-04 $_{4.5e-05}$	4.079e-04 $_{2.4e-04}$	5.770e-04 $_{3.8e-04}$	−
ZDT6	1.374e-02 $_{1.8e-02}$	4.236e-04 $_{1.2e-05}$	4.630e-05 $_{1.6e-02}$	6.773e-04 $_{1.2e-04}$	1.325e-03 $_{2.5e-04}$	+
Kursawe	1.407e-03 $_{1.7e-04}$	1.411e-03 $_{1.7e-04}$	1.754e-03 $_{2.7e-04}$	1.667e-03 $_{1.9e-04}$	1.416e-03 $_{1.4e-04}$	−
Deb2	6.497e-04 $_{9.3e-05}$	7.445e-04 $_{1.5e-01}$	6.561e-04 $_{1.4e-04}$	6.757e-04 $_{1.2e-04}$	8.720e-04 $_{4.9e-02}$	+
Kita	1.973e-03 $_{7.7e-03}$	4.479e-03 $_{2.4e-02}$	1.768e+00 $_{3.6e-02}$	7.527e-03 $_{2.7e-02}$	4.747e-03 $_{1.6e-02}$	+
Constr	4.292e-04 $_{3.8e-05}$	4.346e-04 $_{3.3e-05}$	2.703e-02 $_{5.7e-04}$	4.630e-04 $_{3.8e-05}$	4.931e-04 $_{3.5e-05}$	−
DTLZ1	1.959e-03 $_{3.7e-02}$	2.316e-03 $_{3.5e-02}$	2.549e-03 $_{7.1e-04}$	4.239e-03 $_{2.9e-02}$	6.471e-02 $_{1.8e-01}$	+
DTLZ2	3.461e-03 $_{1.7e-03}$	7.151e-04 $_{7.2e-05}$	3.743e-03 $_{8.9e-04}$	1.354e-03 $_{2.5e-04}$	1.273e-03 $_{2.3e-04}$	+
DTLZ3	5.843e-01 $_{1.1e+00}$	7.216e-01 $_{5.9e-01}$	4.589e-03 $_{1.6e+00}$	8.271e-01 $_{6.5e-01}$	1.594e+00 $_{1.8e+00}$	+
DTLZ4	4.705e-03 $_{2.5e-03}$	4.853e-03 $_{4.4e-04}$	5.707e-03 $_{4.6e-04}$	5.018e-03 $_{4.5e-04}$	4.820e-03 $_{1.4e-03}$	+
DTLZ5	3.231e-04 $_{8.8e-05}$	2.692e-04 $_{3.7e-05}$	2.304e-04 $_{3.8e-05}$	4.510e-03 $_{7.2e-05}$	3.066e-04 $_{4.9e-05}$	+
DTLZ6	4.807e-04 $_{3.2e-05}$	8.250e-02 $_{2.2e-02}$	4.816e-04 $_{3.4e-05}$	1.318e-01 $_{2.0e-02}$	1.230e-01 $_{1.4e-02}$	−
DTLZ7	3.778e-03 $_{1.2e-03}$	1.591e-03 $_{1.3e-03}$	5.226e-03 $_{1.2e-03}$	3.417e-03 $_{8.2e-04}$	3.738e-03 $_{1.5e-03}$	+
Viennet	9.930e-03 $_{1.8e-03}$	1.123e-02 $_{2.3e-03}$	1.104e-02 $_{24e-03}$	1.128e-02 $_{2.6e-03}$	1.319e-02 $_{1.8e-03}$	+
Viennet2	8.851e-04 $_{5.2e-04}$	9.217e-04 $_{5.3e-04}$	9.068e-04 $_{5.0e-04}$	7.753e-04 $_{5.3e-04}$	8.618e-04 $_{3.0e-04}$	−
Viennet3	3.150e-04 $_{1.1e-04}$	6.367e-04 $_{3.2e-04}$	4.578e-04 $_{2.8e-04}$	5.153e-04 $_{1.3e-04}$	6.225e-04 $_{2.2e-04}$	+
Viennet4	1.795e-03 $_{7.8e-04}$	1.568e-03 $_{7.3e-04}$	2.116e-01 $_{2.0e-02}$	2.274e-03 $_{1.1e-03}$	2.752e-03 $_{5.6e-04}$	−
LZ09_F6	9.915e-02 $_{2.8e-01}$	1.236e+00 $_{1.4e+00}$	3.820e+00 $_{2.4e+00}$	1.165e+00 $_{1.2e+00}$	2.735e-01 $_{5.7e-01}$	+
Binh4	5.696e-03 $_{7.6e-04}$	6.171e-02 $_{3.4e-04}$	1.142e+01 $_{5.0e+02}$	6.116e-02 $_{4.3e-04}$	6.204e-02 $_{3.9e-04}$	+
Tamaki	3.716e-03 $_{3.6e-04}$	3.847e-03 $_{3.0e-04}$	7.333e-01 $_{0.0e+00}$	3.766e-03 $_{4.4e-04}$	2.551e-03 $_{3.5e-04}$	+

L. Tang and X. Wang. A hybrid multiobjective evolutionary algorithm for multiobjective optimization problems. ***IEEE Transactions on Evolutionary Computation***, 2013, 17(1): 20-45.

2. System Modeling and Optimization Method

Adaptive Multi-objective Differential Evolution with Reference Axis

Reference Axis Vicinity Mechanism to Guide Evolution Process ⇨ Avoiding local optimum

Restoring Good Distribution of the Population Before Evolution Starting ⇨ Improving diversity

Hybrid Control Strategy for Both Parameters and Mutation Operators ⇨ Accelerating convergence

Performance

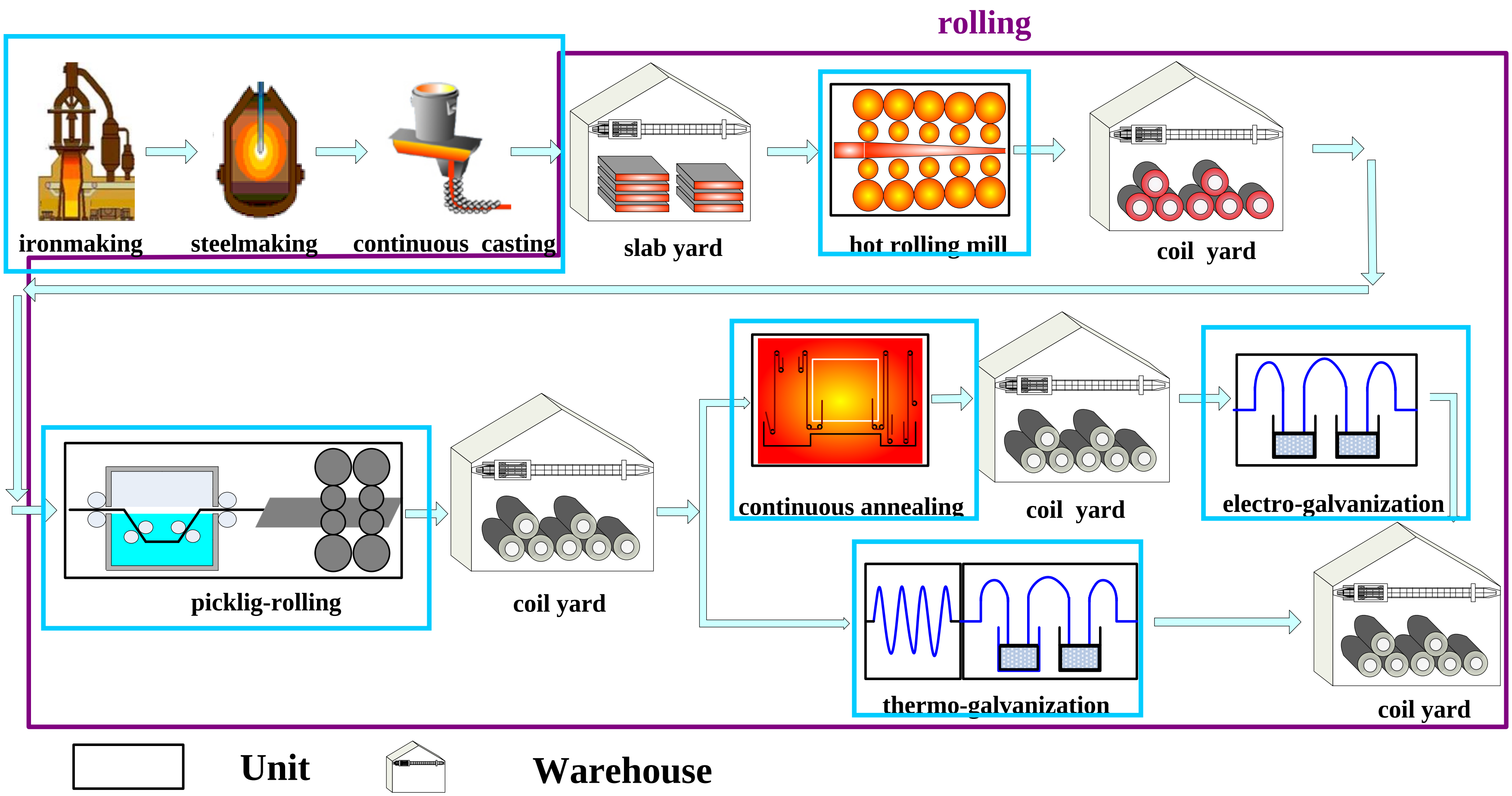
Problems	*GDE3* [20]		*OWMOSaDE* [22]		*MODEA* [23]		*AMPDE* [18]		*GAMODE* [16]		*AMODE-RAVM*	
	Mean	*Std*	*Mean*	*Std*	*Mean*	*Std*	*Mean*	*Std*	*Mean*	*Std*	*Mean*	*Std*
ZDT1	4.514e-03^{+}	1.635e-04	3.896e-03^{+}	5.927e-05	7.638e-03^{+}	8.433e-04	3.768e-03^{+}	2.490e-05	8.699e-03^{+}	7.958e-04	**3.718e-03**	**2.951e-05**
ZDT2	4.574e-03^{+}	1.360e-04	3.985e-03^{+}	5.494e-05	1.121e-02^{+}	1.381e-03	3.890e-03^{+}	3.573e-05	9.252e-03^{+}	1.158e-03	**3.839e-03**	**3.569e-05**
ZDT3	5.082e-03^{+}	1.555e-04	4.443e-03^{-}	9.273e-05	1.007e-02^{+}	1.876e-03	**4.393e-03^{-}**	**7.558e-05**	6.222e-03^{+}	2.324e-04	7.932e-03	2.357e-03
ZDT4	2.582e+00^{+}	6.935e-01	6.551e+00^{+}	1.023e+00	4.758e-02$^{=}$	1.170e-01	**5.616e-03$^{=}$**	**9.912e-03**	6.981e+00^{+}	2.314e+00	**7.331e-03**	**6.473e-03**
ZDT6	4.812e-03^{+}	2.820e-04	3.174e-03^{+}	3.929e-05	4.338e-02^{+}	3.890e-02	3.092e-03^{+}	3.178e-05	4.692e-02^{+}	9.058e-03	**2.295e-03**	**9.645e-05**
DTLZ1	2.529e-02^{+}	9.613e-04	9.357e-01^{+}	1.401e+00	3.232e-02^{+}	2.495e-03	2.364e-02^{+}	1.119e-03	1.350e+00^{+}	8.642e-01	**2.287e-02**	**6.128e-04**
DTLZ2	6.587e-02^{+}	3.092e-03	6.202e-02^{+}	2.352e-03	1.044e-01^{+}	8.194e-03	6.324e-02^{+}	2.633e-03	6.904e-02^{+}	3.873e-03	**6.049e-02**	**1.417e-03**
DTLZ3	1.187e+01^{+}	2.898e+00	2.936e+01^{+}	1.213e+01	3.309e-01^{+}	4.112e-01	6.453e-02$^{=}$	2.788e-03	7.147e+01^{+}	1.640e+01	**6.352e-02**	**2.887e-03**
DTLZ4	6.863e-02^{+}	5.094e-03	**5.234e-02^{-}**	**6.109e-03**	8.399e-02^{+}	2.859e-02	7.176e-02$^{=}$	4.097e-02	5.323e-02$^{=}$	2.842e-02	6.242e-02	4.315e-03
DTLZ5	5.409e-03^{+}	2.302e-04	**4.100e-03^{-}**	**9.596e-05**	3.130e-02^{+}	4.410e-03	4.101e-03^{-}	7.717e-05	4.821e-03^{+}	1.812e-04	4.270e-03	1.168e-04
DTLZ6	5.699e-03^{+}	2.496e-04	4.014e-03^{+}	1.116e-04	2.773e-02^{+}	9.969e-03	4.049e-03^{+}	1.581e-04	3.149e+00^{+}	2.789e-01	**3.897e-03**	**1.017e-04**
DTLZ7	**7.630e-02$^{=}$**	**4.380e-03**	7.665e-02$^{=}$	5.365e-03	1.442e-01^{+}	2.278e-02	8.956e-02$^{=}$	6.783e-02	1.217e-01^{+}	1.052e-01	7.722e-02	2.845e-03
LZ_09_F1	3.963e-02^{+}	1.432e-02	3.209e-02^{+}	1.728e-02	7.163e-02^{+}	1.121e-02	1.703e-02^{+}	1.112e-02	8.042e-03$^{=}$	9.767e-04	**7.754e-03**	**3.716e-04**
LZ_09_F2	8.828e-02^{+}	8.945e-03	1.027e-01^{+}	3.584e-02	1.035e-01^{+}	1.480e-02	1.057e-01^{+}	2.295e-02	1.012e-01^{+}	2.502e-03	**5.576e-02**	**1.183e-02**
LZ_09_F3	6.459e-02^{+}	6.251e-03	6.672e-02^{+}	1.158e-02	8.160e-02^{+}	1.246e-02	7.832e-02^{+}	1.183e-02	5.664e-02^{+}	1.086e-03	**3.054e-02**	**5.348e-03**
LZ_09_F4	6.713e-02^{+}	2.816e-03	7.441e-02^{+}	1.186e-02	7.809e-02^{+}	5.984e-03	5.220e-02^{+}	6.493e-03	6.112e-02^{+}	1.313e-03	**2.910e-02**	**6.019e-03**
LZ_09_F5	5.131e-02^{+}	2.937e-03	6.062e-02^{+}	7.005e-03	6.353e-02^{+}	4.926e-03	6.054e-02^{+}	1.650e-02	4.440e-02^{+}	2.014e-03	**2.297e-02**	**4.626e-03**
LZ_09_F6	1.708e-01^{+}	6.567e-02	2.438e-01^{+}	8.019e-02	2.767e-01^{+}	3.751e-02	1.754e-01^{+}	6.278e-02	1.807e-01^{+}	5.758e-03	**1.159e-01**	**8.039e-03**
LZ_09_F7	4.032e-01^{+}	9.481e-02	5.763e-01^{+}	6.624e-02	2.186e-01$^{=}$	4.992e-02	3.547e-01^{+}	8.085e-02	**1.726e-01$^{=}$**	**4.235e-02**	2.129e-01	1.189e-01
LZ_09_F8	4.643e-01^{+}	5.716e-02	4.522e-01^{+}	1.524e-01	2.632e-01^{+}	4.250e-02	3.126e-01^{+}	7.166e-02	2.671e-01^{+}	7.849e-02	**2.059e-01**	**5.913e-02**
LZ_09_F9	1.490e-01^{+}	9.287e-02	1.080e-01^{+}	8.482e-03	1.319e-01^{+}	5.207e-02	1.086e-01^{+}	3.458e-02	1.080e-01^{+}	2.641e-03	**7.287e-02**	**1.838e-02**
UF1	8.909e-02^{+}	9.930e-03	8.795e-02^{+}	1.305e-02	9.959e-02^{+}	1.406e-02	9.190e-02^{+}	3.295e-02	8.574e-02^{+}	1.912e-02	**5.524e-02**	**1.153e-02**
UF2	5.179e-02^{+}	2.867e-03	6.249e-02^{+}	8.821e-03	6.641e-02^{+}	7.271e-03	5.023e-02^{+}	8.377e-03	3.232e-02^{+}	7.543e-03	**2.343e-02**	**3.944e-03**
UF3	3.829e-01^{+}	6.132e-03	3.400e-01^{+}	3.798e-02	3.309e-01^{+}	1.320e-02	1.479e-01$^{=}$	4.705e-02	2.270e-01^{+}	3.766e-02	**1.457e-01**	**1.695e-02**
UF4	5.098e-02^{+}	2.215e-03	5.433e-02^{+}	2.191e-03	5.444e-02^{+}	4.813e-03	4.725e-02^{+}	9.031e-04	7.307e-02^{+}	3.772e-03	**4.519e-02**	**9.668e-04**
UF5	3.589e-01^{+}	1.498e-01	5.916e-01^{+}	1.164e-01	2.806e-01$^{=}$	6.531e-02	3.410e-01^{+}	8.073e-02	3.989e-01^{+}	9.579e-02	**2.555e-01**	**7.925e-02**
UF6	1.894e-01$^{=}$	8.420e-02	4.532e-01^{+}	6.626e-02	2.367e-01$^{=}$	1.520e-01	2.398e-01$^{=}$	6.921e-02	**1.798e-01$^{=}$**	**5.394e-02**	2.058e-01	1.412e-01
UF7	4.725e-02^{+}	1.032e-02	5.631e-02^{+}	6.806e-03	6.482e-02^{+}	6.089e-02	4.671e-02^{+}	1.026e-02	1.347e-01^{+}	1.236e-01	**2.557e-02**	**3.010e-03**
UF8	3.148e-01^{+}	2.319e-02	3.957e-01^{+}	9.287e-02	3.379e-01^{+}	3.394e-02	2.072e-01^{+}	3.817e-02	1.975e-01^{+}	9.073e-03	**1.788e-01**	**2.686e-02**
UF9	2.282e-01^{+}	5.338e-02	5.120e-01^{+}	8.700e-02	3.692e-01^{+}	5.231e-02	**1.548e-01$^{=}$**	**7.305e-02**	1.892e-01^{+}	2.225e-02	1.558e-01	5.124e-02
UF10	4.029e-01^{+}	1.799e-01	1.944e+00^{+}	3.597e-01	4.222e-01^{+}	1.071e-01	3.058e-01$^{=}$	2.453e-01	1.282e+00^{+}	4.241e-01	**2.530e-01**	**7.129e-02**
Nos. + / = / –	29 / 2 / 0		27 / 1 / 3		27 / 4 / 0		21 / 8 / 2		27 / 4 / 0			

L. Tang, X. Wang, and Z. Dong. Adaptive multiobjective differential evolution with reference axis vicinity mechanism. ***IEEE Transactions on Cybernetics***, 2019, 49(9): 3571-3585.

Outline

- Research Background
- System Modeling and Optimization Method
- **Production Scheduling**
- Logistics Scheduling
- Energy Optimization
- Data Analytics

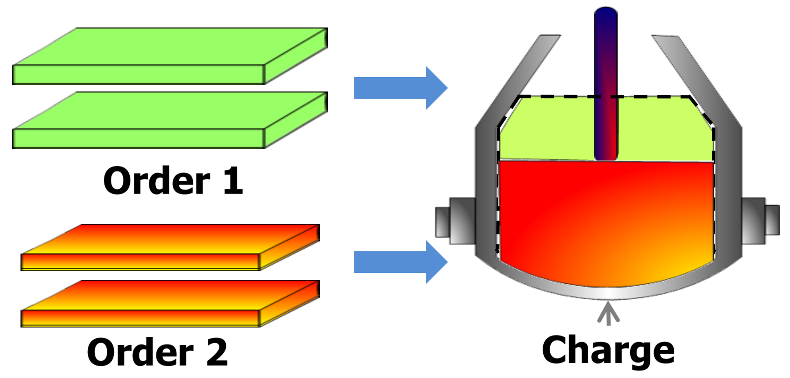
3. Production Scheduling —— Steel Production



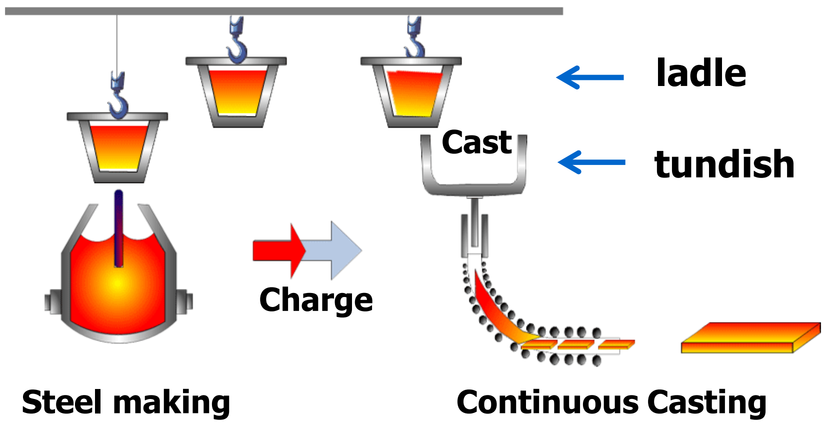
Production: Iron-making/Steelmaking/Hot Rolling/Cold Rolling

3. Production Scheduling —— Steelmaking Stage

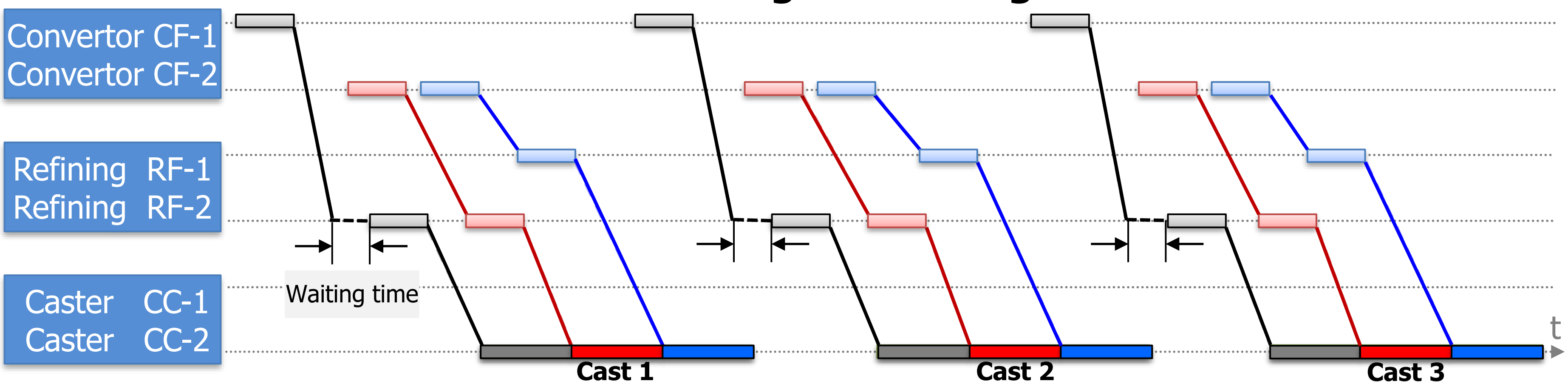
Charge Batching



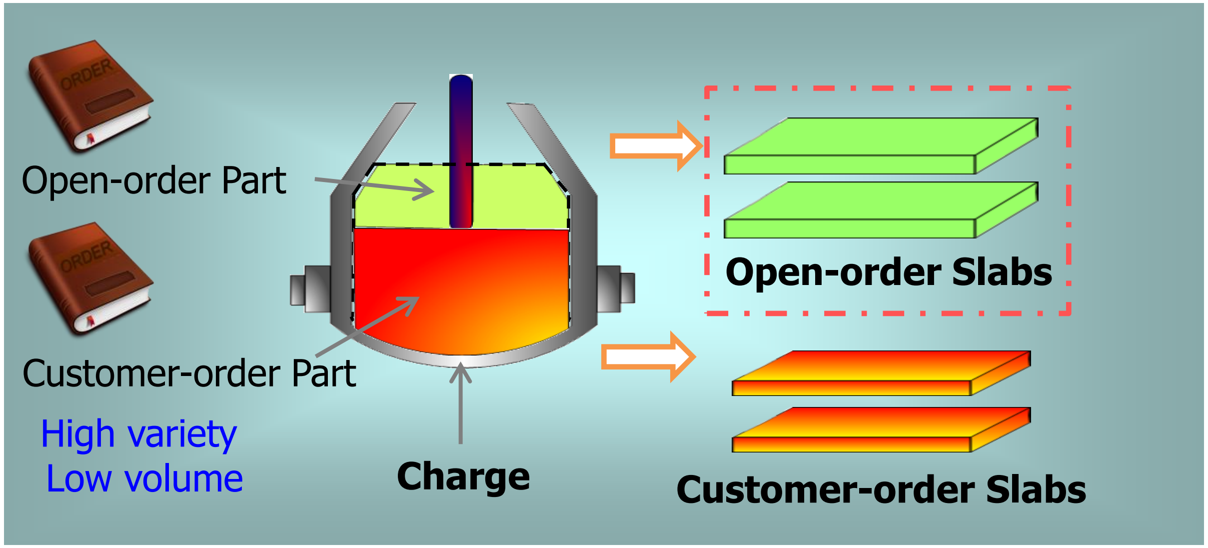
Cast Batching

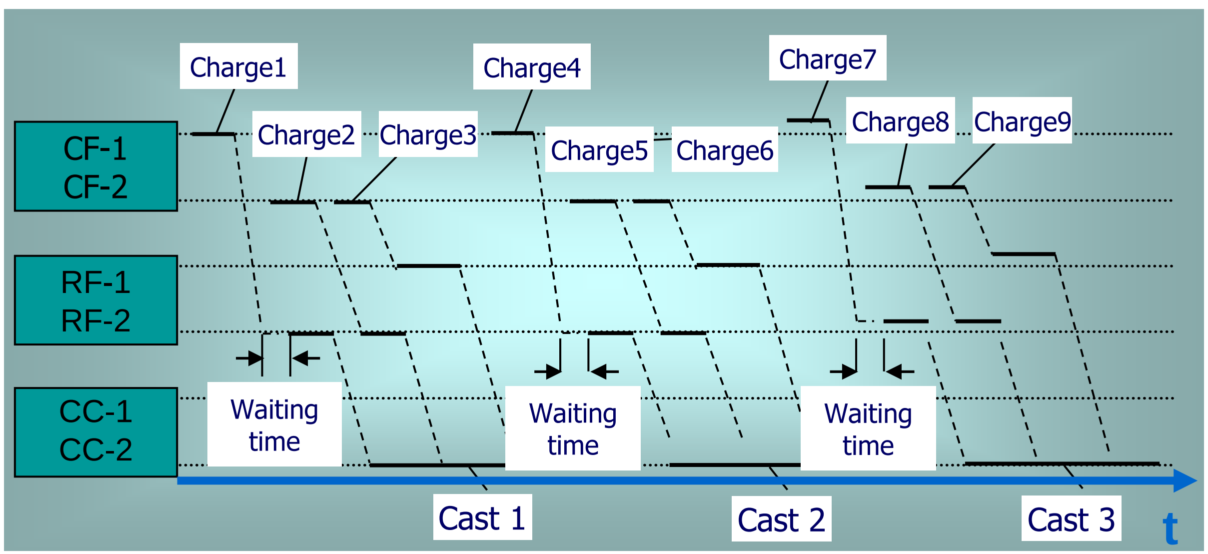


Steelmaking Scheduling



3. Production Scheduling —— Charge Batching of Steelmaking





Group all the slabs of different customer orders into batches

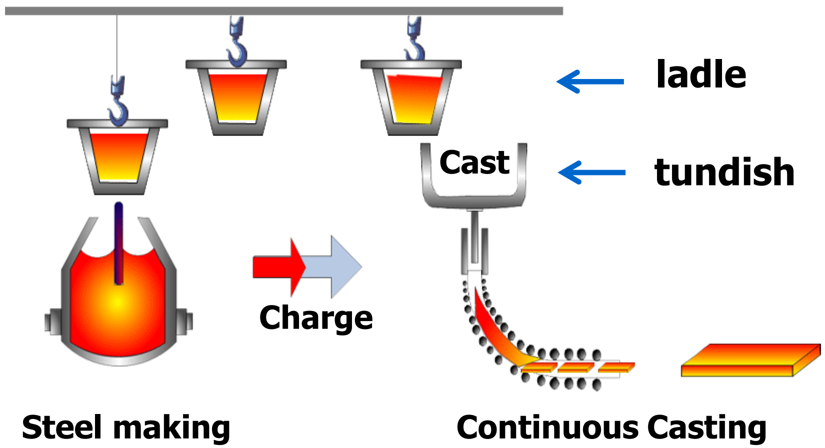
p-median clustering with capacity and additional technical constraints

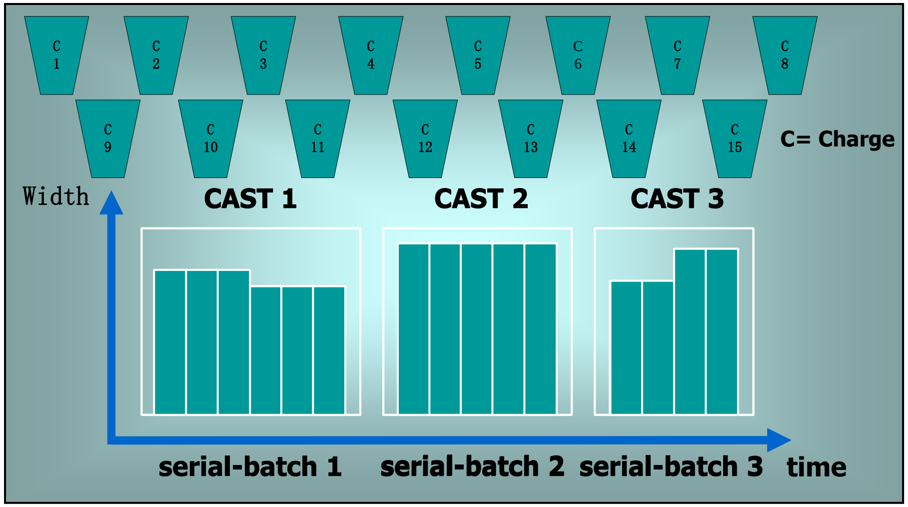
- Minimize assignment cost
- Minimize open-order slabs
- Minimize unfulfilled cost of order

- Lagrangian relaxation
- Column generation

L. Tang, G. Wang, J. Liu, J. Liu. A combination of Lagrangian relaxation and column generation for order batching in steelmaking and continuous-casting production. ***Naval Research Logistics***, 2011, 58(4): 370-388.

3. Production Scheduling —— Cast Batching of Steelmaking





Decisions

- Batch and sequence charges to form casts for the given tundishes
- Select a casting width for each charge in a cast

Objectives

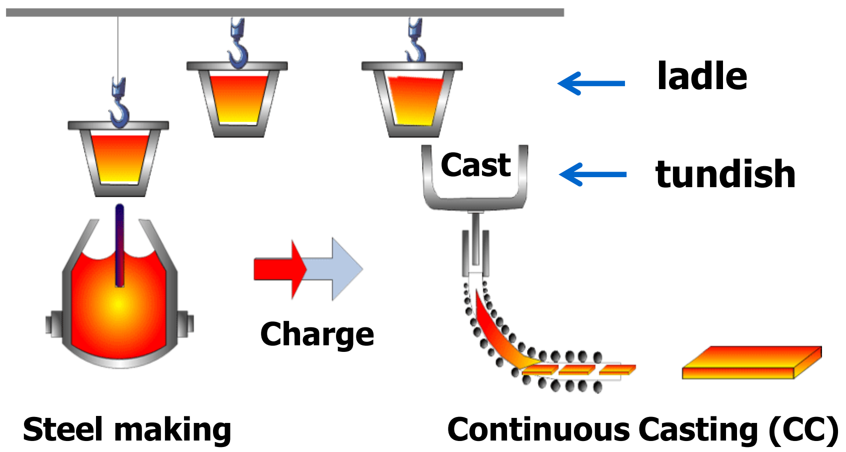
- Maximize tundish utilization
- Minimize total grade switch and width switch cost

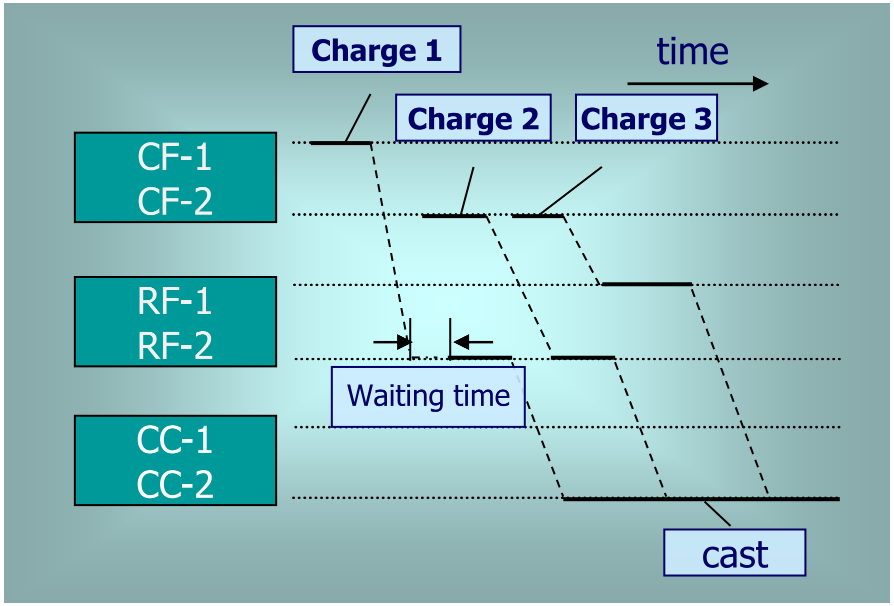
Constraints

- Grade switch constraint
- Width switch constraint
- Lifespan of tundish

L. Tang, G. Wang, Z. Chen. Integrated charge batching and casting width selection at Baosteel. ***Operations Research***, 2014, 62(4): 772-787.

3. Production Scheduling —— Steelmaking Scheduling





Just-in-time idea

Solve machine conflicts in (SCC) production scheduling based on JIT idea

Four-level scheduling

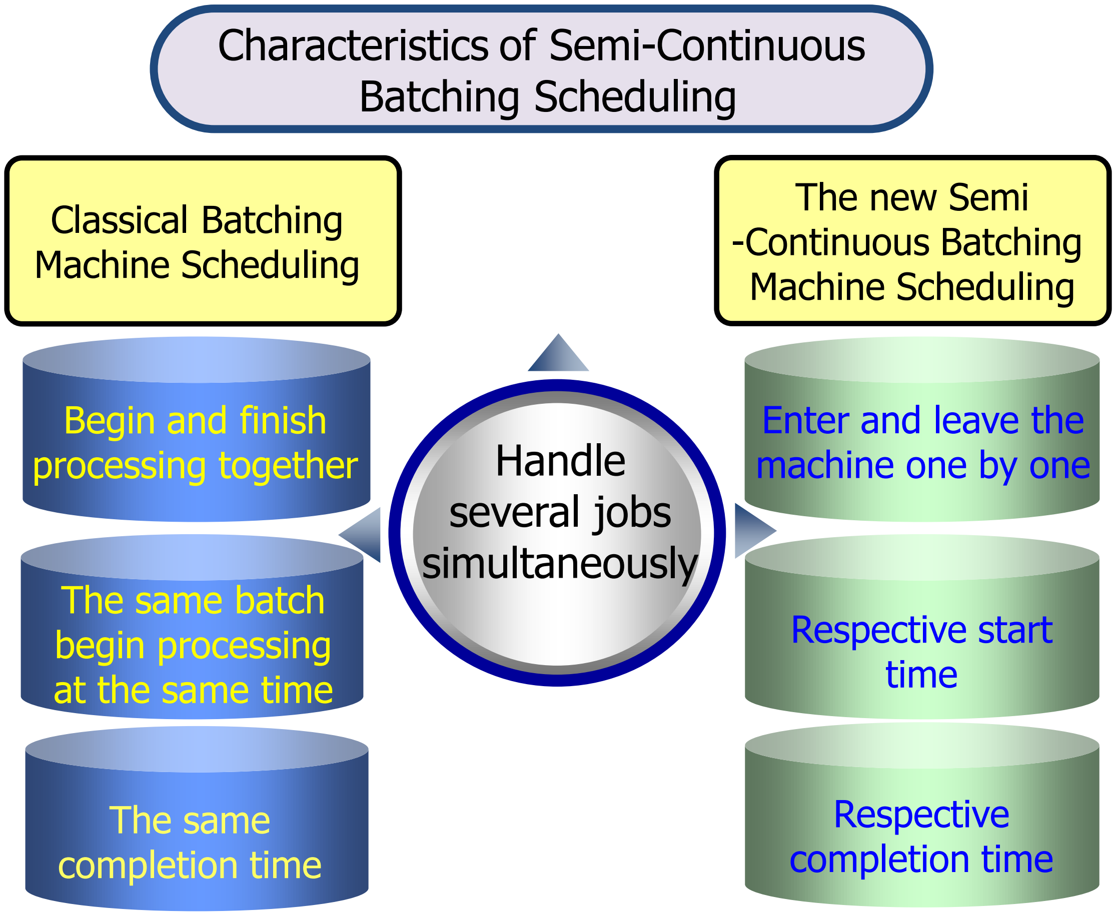
- Level 1: cast sequences on the casters
- Level 2: sub-scheduling
- Level 3: rough scheduling
- Level 4: elimination of machine conflicts

Beneficial effects

- Improve productivity of large devices
- Shorten waiting-time between operations
- Cut down production costs

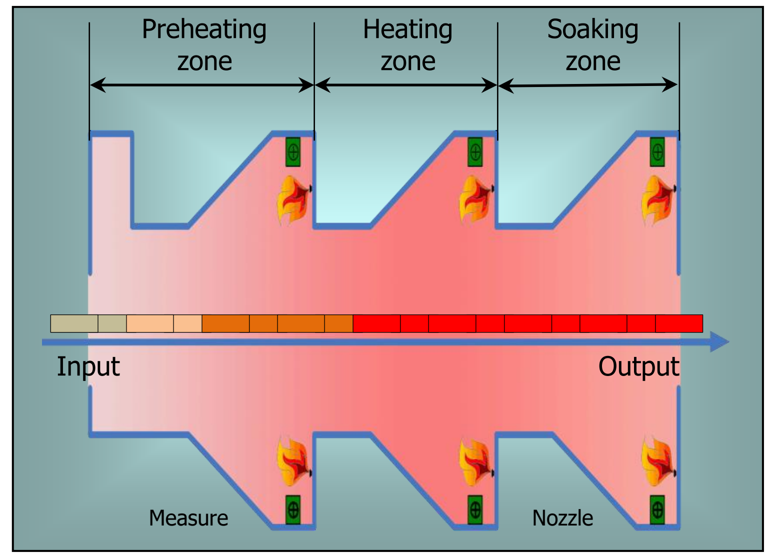
L. Tang, J. Liu, A. Rong, Z. Yang. A mathematical programming model for scheduling steelmaking-continuous casting production. ***European Journal of Operational Research***, 2000, 120(2): 423-435.

3. Production Scheduling —— Semi-continuous Batch Scheduling



Traditional batching machines are mainly divided into three types: (1) burn-in (2) fixed batch (3) serial batching

- A new kind of batch scheduling
- We analyze the semi-continuous batch scheduling problem, and present optimal algorithm



The heating process of Tube-billets in heating furnace

L. Tang, Y. Zhao. Scheduling a single semi-continuous batching machine. ***Omega***, 2008, 36(6):992-1004.

3. Production Scheduling —— Hot Rolling Scheduling

Decision	Objective
Sequence of adjacent jobs to be processed	Minimize the total changeover costs

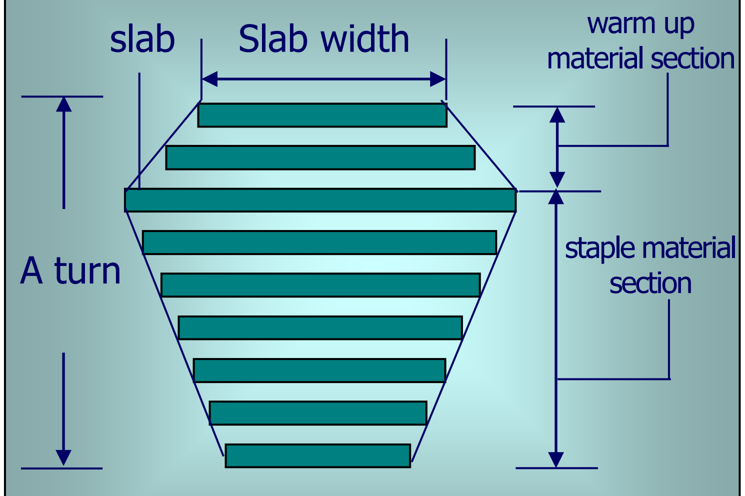
Minimize $\sum_{i=1}^{N+M} \sum_{j=1}^{N+M} C_{ij} X_{ij}$

Subject to

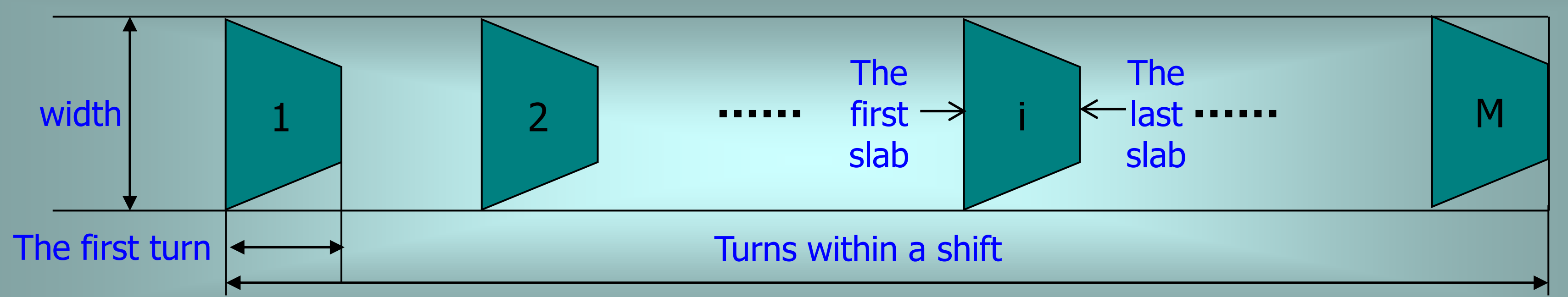
$$\sum_{i=1}^{N+M} X_{ij} = 1, \quad j \in \{1, 2, ..., N+M\}$$

$$\sum_{j=1}^{N+M} X_{ij} = 1, \quad i \in \{1, 2, ..., N+M\}$$

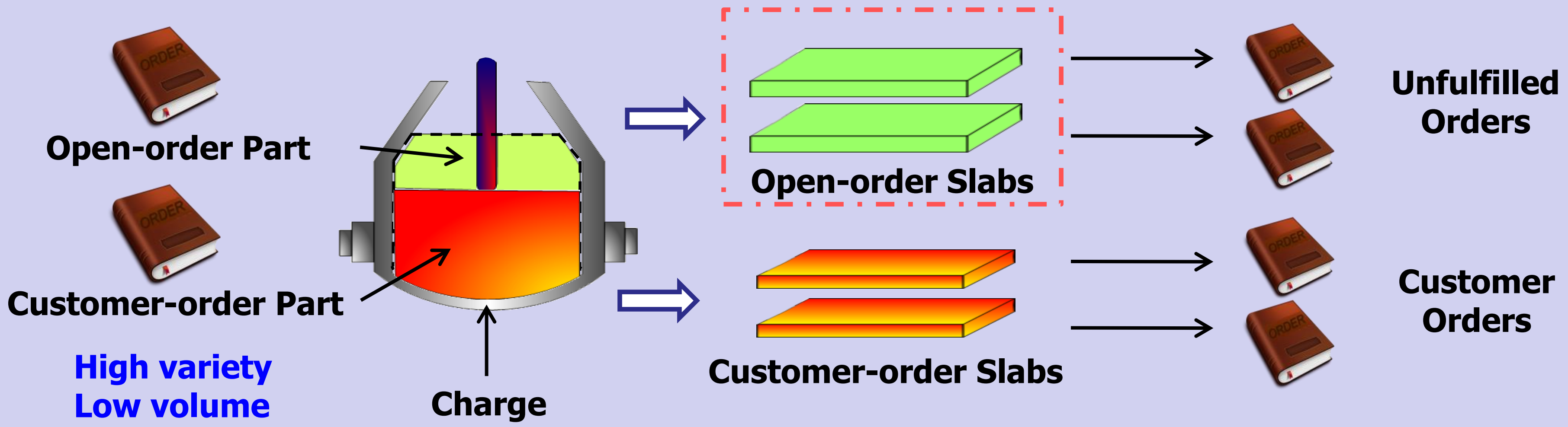
$$\sum_{i \in S} \sum_{j \in S \setminus \{i\}} X_{ij} \le |S| - 1, \quad S \subset \{1, ..., N+M\}, \; 2 \le |S| \le N+M-2$$

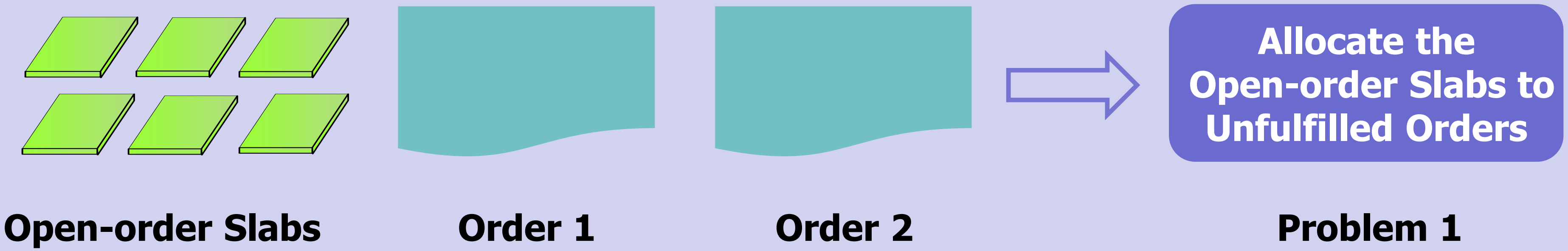


Structure and components of a turn



3. Production Scheduling —— Slab Allocation at Hot Rolling Stage





This work was awarded INFORMS Franz Edelman Award Finalist, 2013

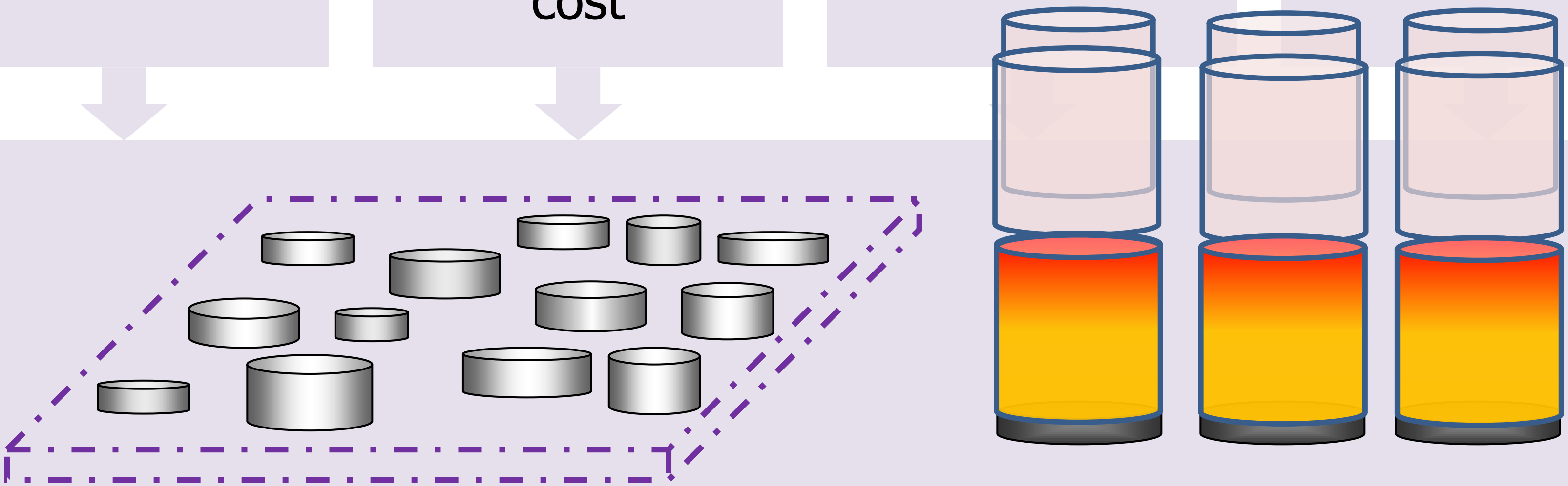
3. Production Scheduling —— Parallel Batch Scheduling at Cold Rolling

Maximize Reward

Minimize Mismatching cost

Equipment Constraints

Matching Constraints



Form batches for each empty furnace

Select a median coil for each batch

L. Tang, Y. Meng, Z. Chen, J. Liu. Coil batching to improve productivity and energy utilization in steel production. ***Manufacturing & Service Operations Management***, 2016, 18(2): 262-279.

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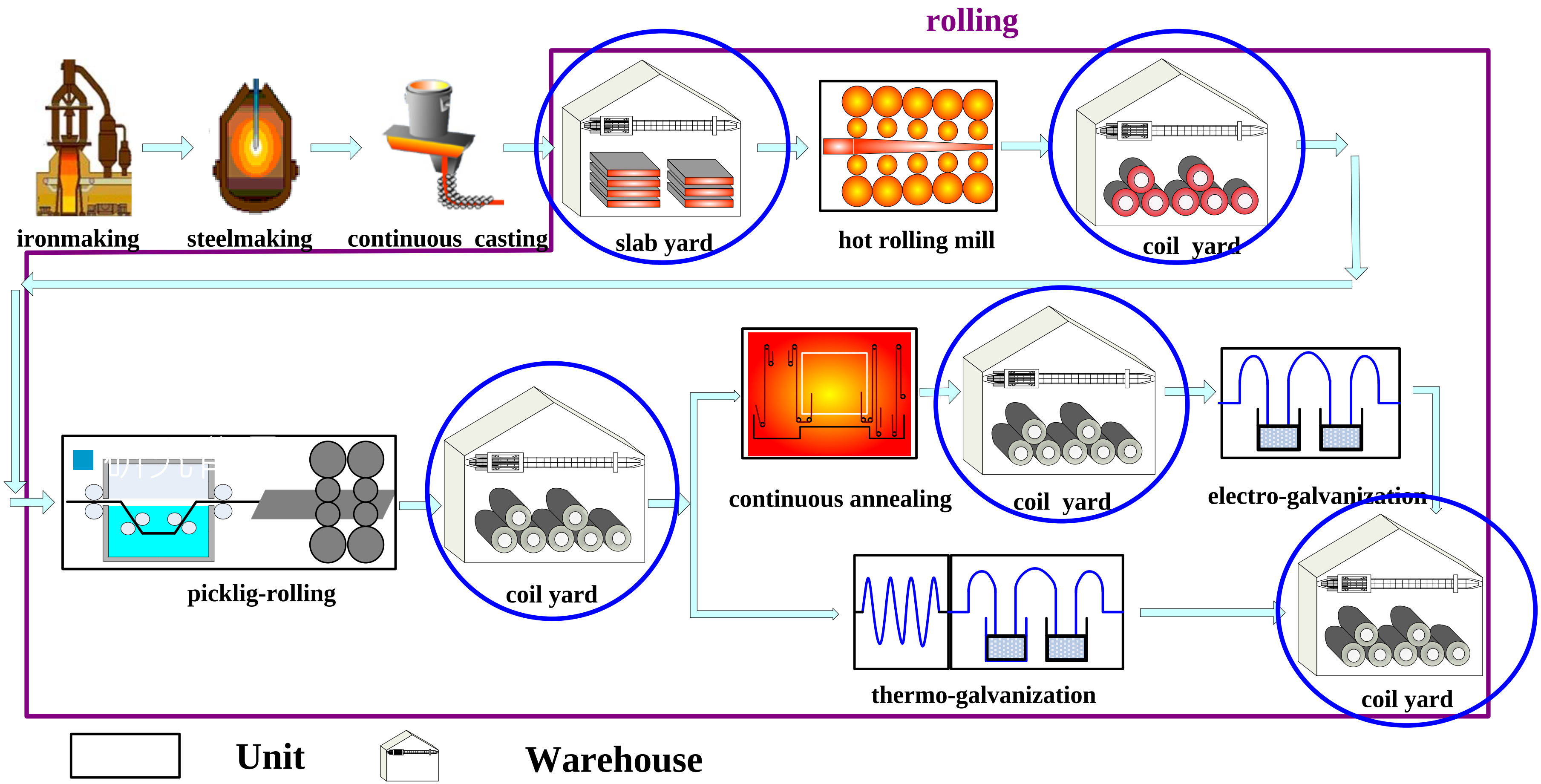
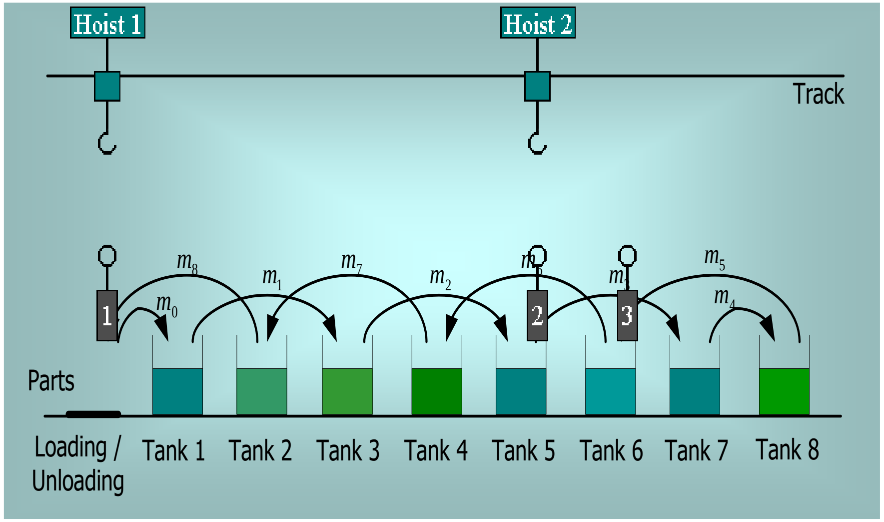
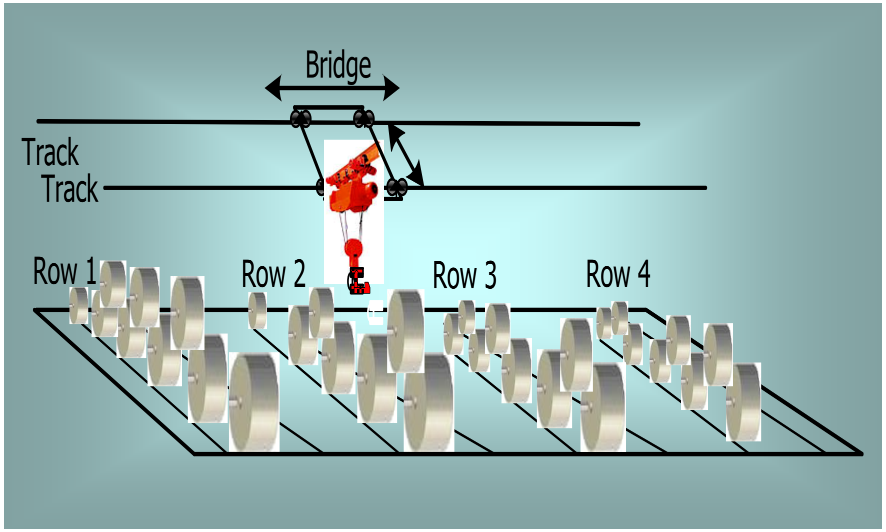
- **Logistics Scheduling**
- Energy Optimization
- Data Analytics



Logistics: (Un)Loading/Transportation/Shuffling/Storage/Stowage

4. Logistics Scheduling —— Crane Scheduling in Loading Operation





Crane scheduling problem

Determines the transportation sequence for all demanded coils and shuffled position for each blocking coil.

Decisions

Retrieval sequence of the target coils and shuffled positions for blocking coils

Objectives

Minimize the time by which the retrieval of all target coils is completed

For general case

Heuristic algorithm & worst-case analysis

For special cases

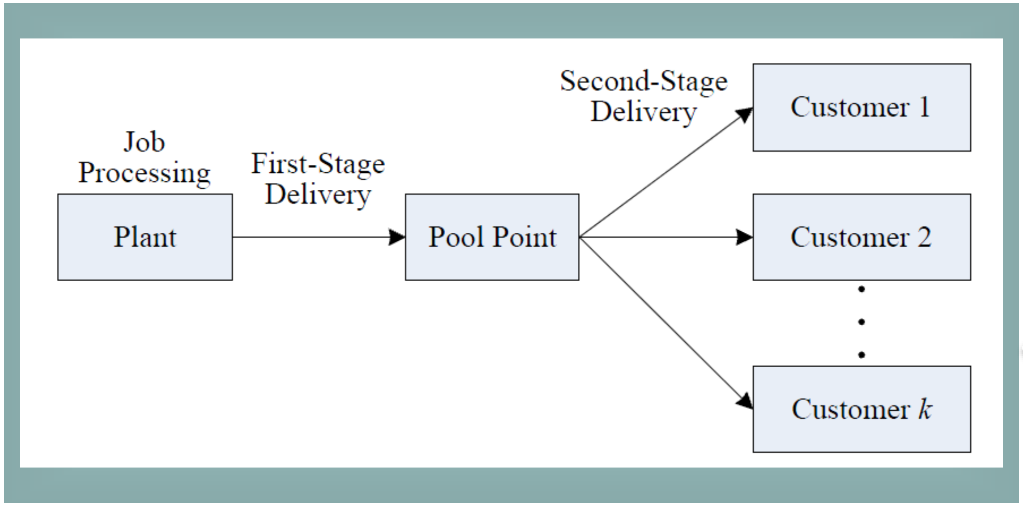
Polynomial algorithms (optimal solutions)

L. Tang, X. Xie, J. Liu. Crane scheduling in a warehouse storing steel coils. ***IISE Transactions***, 2014, 46(3): 267-282.

4. Logistics Scheduling —— Coordinated Transportation Scheduling

Integrated Production & Two-Stage Distribution Scheduling

- Obtain a joint schedule of job processing at the plant and two-stage shipping
- Optimize a performance measure that takes into account both delivery timeliness and total transportation costs



Offline problems involving a single production line

- Optimal dynamic programming algorithms

Offline problems involving multiple production lines

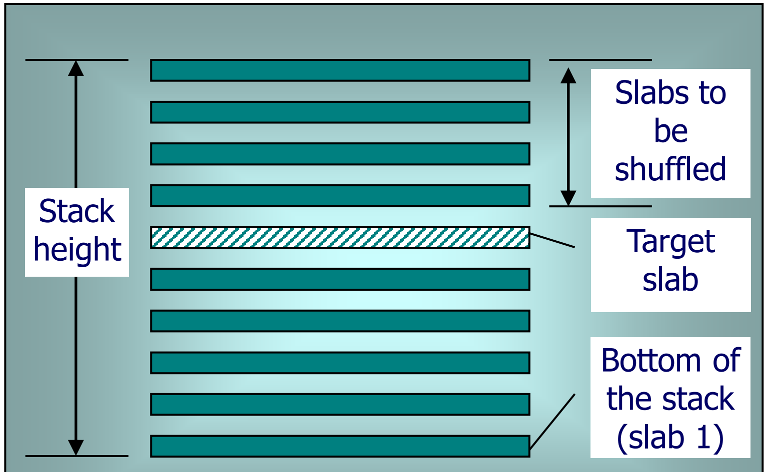
- Fast heuristics
- Worst-case & asymptotic performance

Online problems

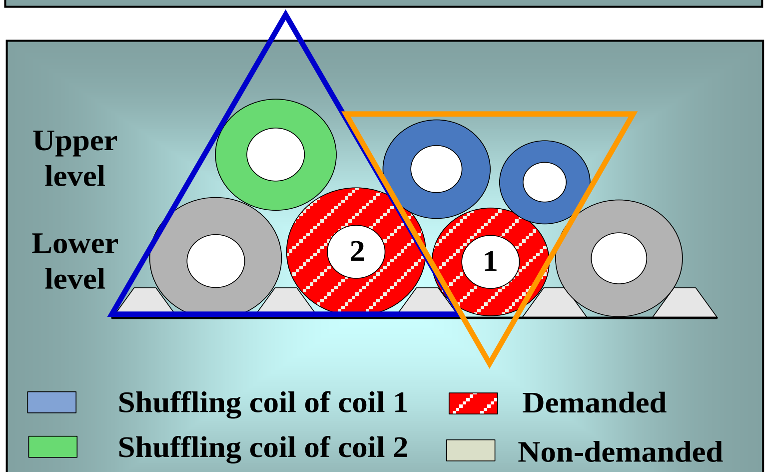
- Online algorithms
- Competitive ratios analytics

L. Tang, F. Li, Z. Chen. Integrated scheduling of production and two-stage delivery of make-to-order products: offline and online algorithms. ***INFORMS Journal on Computing***, 2019, 31(3):493-514.

4. Logistics Scheduling —— Shuffling



The structure of a slab stack



The structure of a coil stack

Shuffling Problems in Steel Plants

Assign a storage slot for each shuffled item during retrieving all target items in the given sequence

Decisions

Suitable storage positions for shuffled items

Objectives

Minimize shuffling and crane traveling

For general case

Greedy heuristic

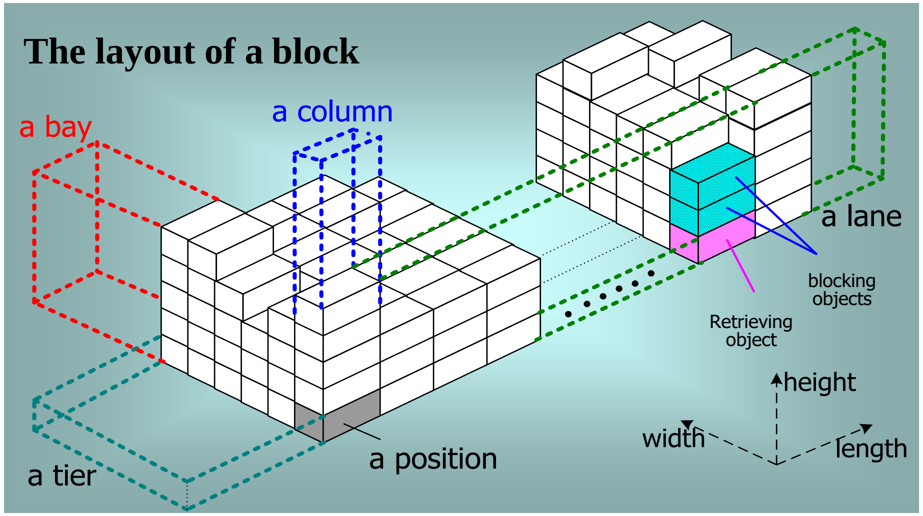
For special cases

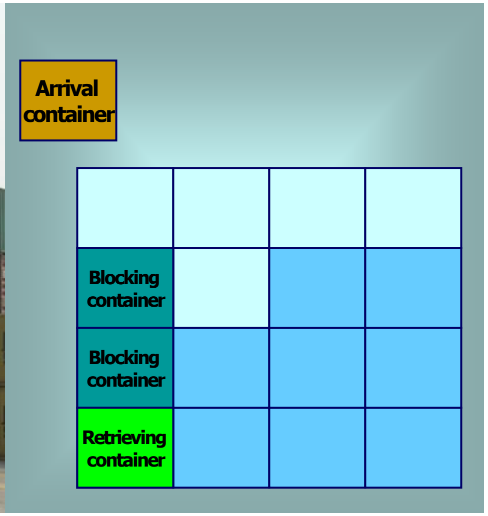
Polynomial algorithms (optimal solutions)

L. Tang, R. Zhao, J. Liu. Models and algorithms for shuffling problems in steel plants. ***Naval Research Logistics***, 2012, 59(7): 502-524.

4. Logistics Scheduling —— Reshuffling and Stacking

- For statistic and dynamic reshuffling problem, an improved mathematical formulation and a simulation model are established, respectively；
- Five polynomial time heuristics and their extended versions are proposed and analyzed theoretically；
- The proposed heuristic outperforms existing methods.





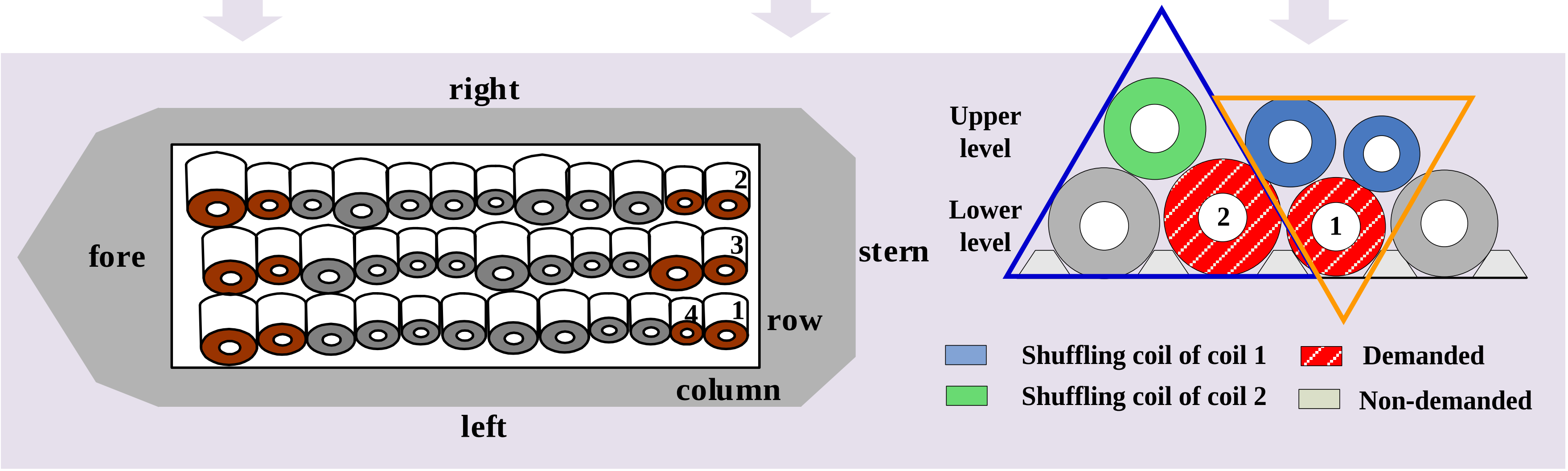
L. Tang, W. Jiang, J. Liu, Y. Dong. Research into container reshuffling and stacking problems in container terminal yards. ***IISE Transactions***, 2015, 47(7): 751-766. (**IISE Transactions Best Applications Paper Award**)

4. Logistics Scheduling —— Ship Stowage Planning

Minimize the moment imbalance

Minimize the shuffling

Minimize the dispersion of coils for the same destination



Structural constraints

Weight restriction constraints

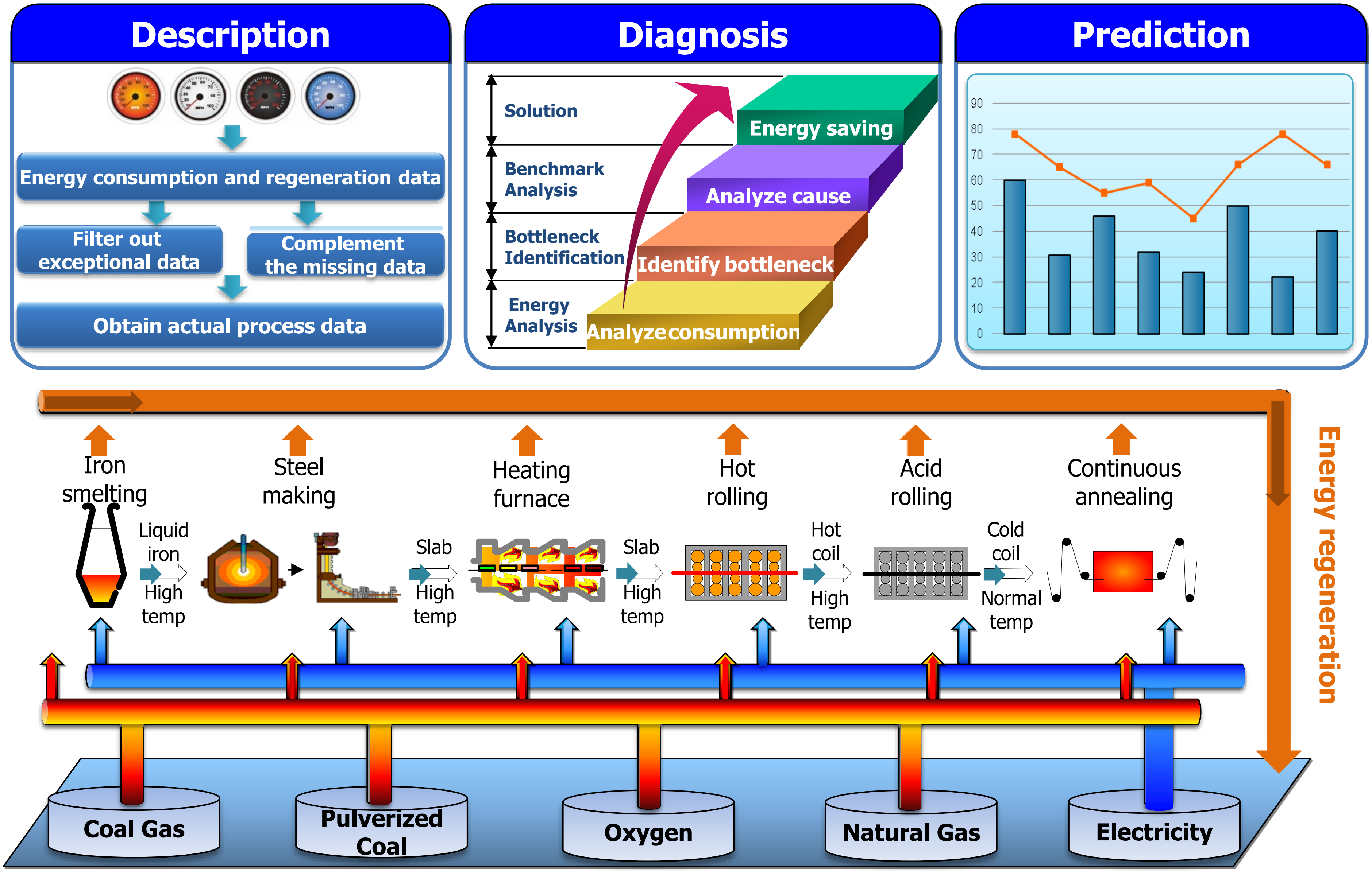
Operational constraints

L. Tang, J. Liu, et al. Modeling and solution for the ship stowage planning Modeling and solution for the ship stowage planning problem of coils in the steel industry. ***Naval Research Logistics***, 2015, 62(7): 564-581.

Outline

- Research Background
- System Modeling and Optimization Method
- Production Scheduling
- Logistics Scheduling
- **Energy Optimization**
- Data Analytics

5. Energy Optimization —— Energy Analytics



5. Energy Optimization —— Dynamic Energy Allocation

Objectives

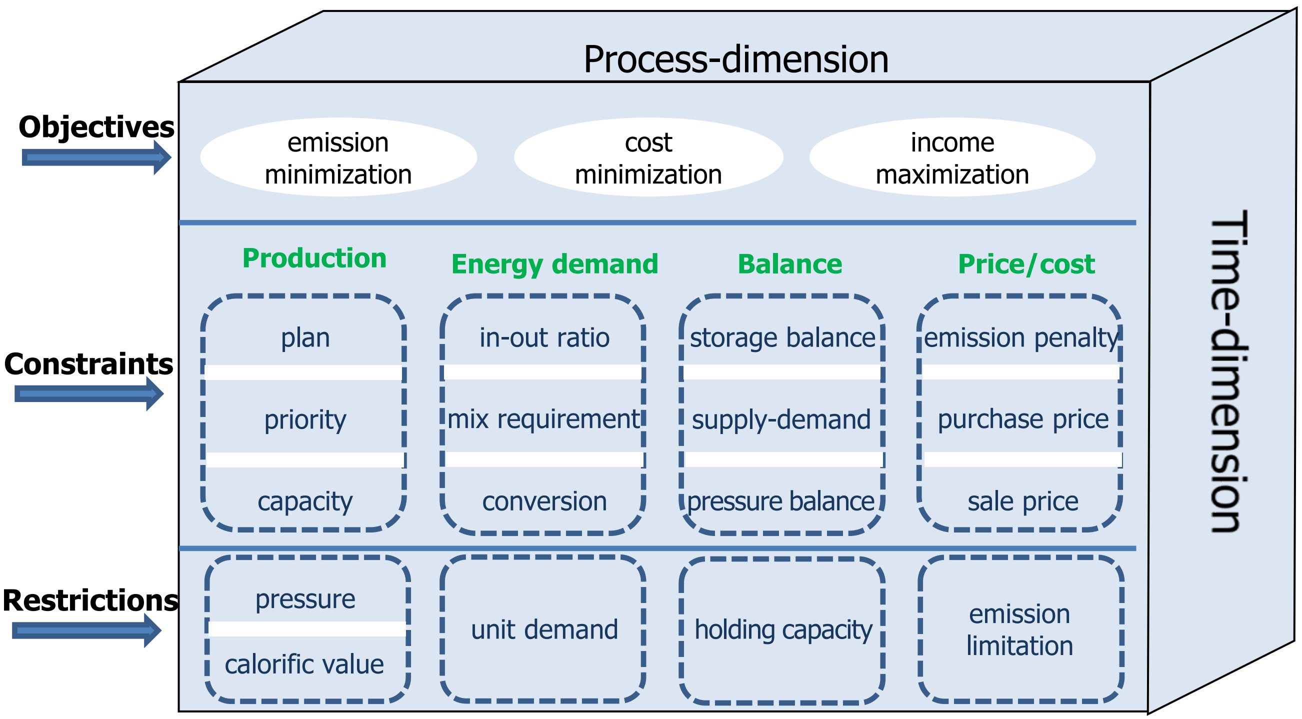
- Minimizing emission
- Minimizing cost
- Maximizing income

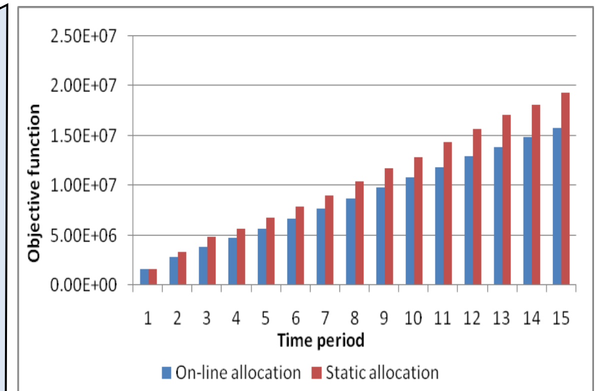
Constraints

- Production
- Balance
- Demand
- Price

ADP Algorithm

Accomplish dynamic energy allocation





- The proposed energy allocation method shows obvious superiority in terms of effectiveness and stability than static method.

5. Energy Optimization —— Gas Allocation

Comprehensive allocation of gas system

- **Determine**: allocation plan of BFG, COG, LDG
- **Multi-objective:** minimizing consumption cost, purchase cost, emission cost, energy holding cost
- **Solution method:** soft constraint handling NSGA-II

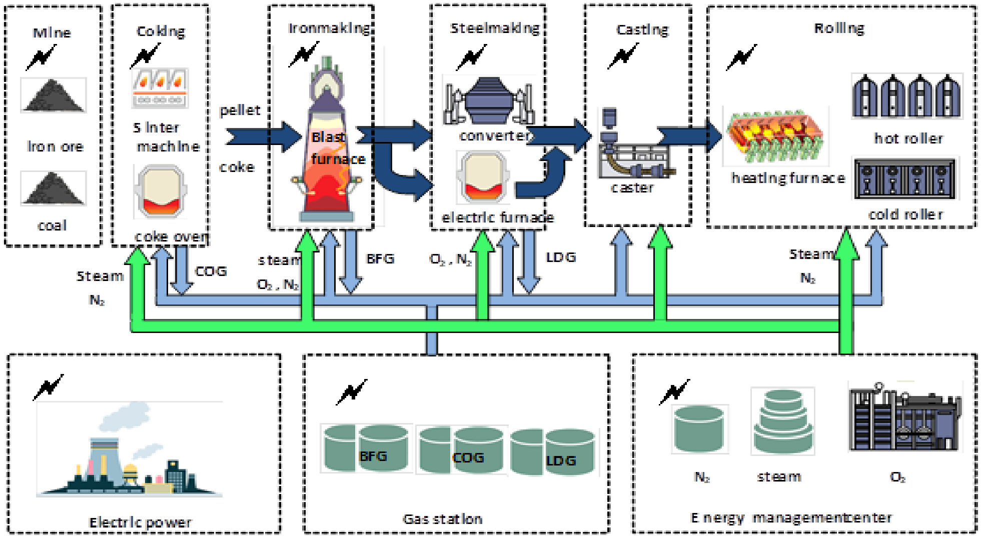
$$\sum_i x_i + w \le \sum_i y_i + z + \left(H - H^0\right)$$

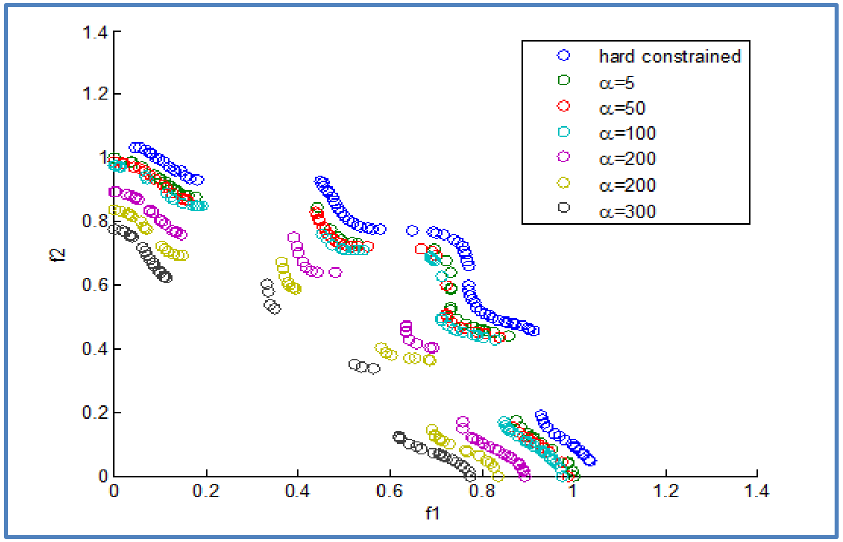
$$y_i \le \theta_i^1 p_i, i = 1, 2, ..., I$$

⇨ Constraint Definition

$$\mu(G) = \begin{cases} 0 & G \le \delta \\ 1\text{-}e^{-\left(\frac{G-\delta}{\alpha}\right)} & G > \delta \end{cases}$$

⇨ Soft Constraint Definition



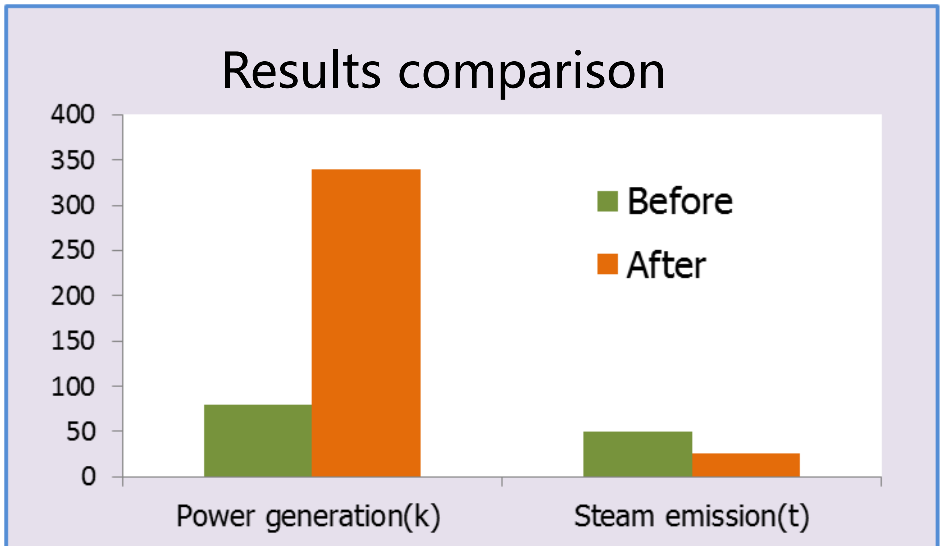


Y. Zhang, G. G. Yen, and L. Tang. Soft constraint handling for a real-world multiobjective energy distribution problem. ***International Journal of Production Research***, 2020, 58(19): 6061-6077.

5. Energy Optimization —— Steam Scheduling

Steam scheduling by coordinating demand and electricity generation

User demand → **Make full use of excess steam resources** ← Electricity generation



Objectives

- Maximize electricity generation upon demand

$$z = \max \sum_t \sum_i \left(u_i + v_i x_{ti,j=1} + w_i R_{ti}\right)$$

Supply capacity constraints

$$a_i^0 < \sum_{j=1}^{4} x_{tij} < a_i^1,\ b_{ij}^0 \le x_{tij} \le b_{ij}^1,\ r_i^0 \le R_{ti} \le \min\left(x_{ti1}, r_i^1\right),\ q_i^0 \le Q_{ti} \le \min\left(x_{ti1}, q_i^1\right)$$

$$x_{tij} = \min\left\{a_i^1, \max\left(a_i^0, S_t^D - \sum_{i\in I_1\cup I_2\cup I_3}\left(x_{ti,3} + R_{ti} + Q_{ti}\right)\right)\right\}$$

Fluctuation, safe flow constraints

$$F_t^D = \max\left(0, \sum_i \sum_{j\in J_3}\left(x_{tij} + R_{ti} + Q_{ti}\right) - e^D\right) \quad F_t^Z = \max\left(0, \sum_i x_{tij} - e^Z\right)$$

$$\left|\sum_i \sum_j \left(x_{tij} + R_{ti} + Q_{ti}\right) - \sum_i \sum_{j\in J_3}\left(x_{t-1,ij} + R_{t-1,i} + Q_{t-1,i}\right)\right| \le \delta^D$$

Steam demand constraints

$$\eta^Z \sum_i x_{tij} > S_t^Z \qquad \eta^D \sum_i \sum_j \left(x_{tij} + R_{ti} + Q_{ti}\right) > S_t^D$$

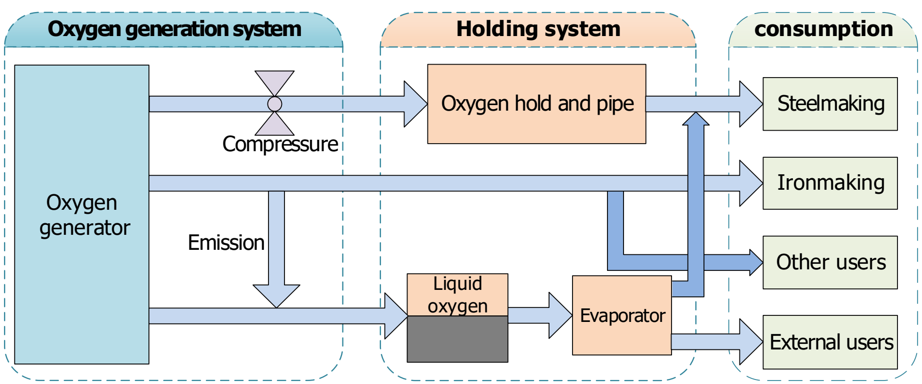
5. Energy Optimization —— Oxygen Scheduling

Task

Dynamically balance and optimize the oxygen system

Supply Modes

- Supplied by oxygen generator
- Supplied by liquid oxygen system



Minimize operating cost of oxygen system

$$Z = \sum_t \sum_{i\in E} \left(c_i \cdot F_{ti} + c_i^A \cdot A_{ti} + c_i^Y \cdot Y_{ti} + \frac{1}{2}\gamma_{ti} \cdot c_i \cdot 0.7B_i \right)$$

Oxygen generators capacity, operating requirements

$$\left|O_{ti} - O_{t-1,i}\right| \le \beta_{ti}\varepsilon \qquad G_{ti} = G_{t-1,i} + Y_{ti} - D_{ti}, \qquad G_i^0 \le G_{ti} \le G_i^1,$$

$$\gamma_{ti} = \max\left\{0, \left(\beta_{ti} - \beta_{t-1,i}\right)\right\} \qquad d_t = \sum_{i\in E} D_{ti}, \qquad d_t < \sum_{i\in E} G_{t-1,i}$$

Pipeline pressure, fluctuation limitations

$$\left(H_t - H_{t-1}\right) + \sum_{j=1} S_{tj} < \sum_{i\in E} A_{ti} \qquad H^0 \le H_t \le H^1$$

$$\left|\frac{H_t - H_{t-1}}{H_{t-1}}\right| \le \delta \qquad A_{ti} \le \beta_{ti} a_i \qquad A_{ti} < O_{ti}$$

Oxygen demand constraints

$$\sum_j S_{tj} + \sum_{i\in E} Y_{ti} + \left(H_t - H_{t-1}\right) + F_t = \sum_{i\in E} O_{ti}$$

Outline

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- **Data Analytics**

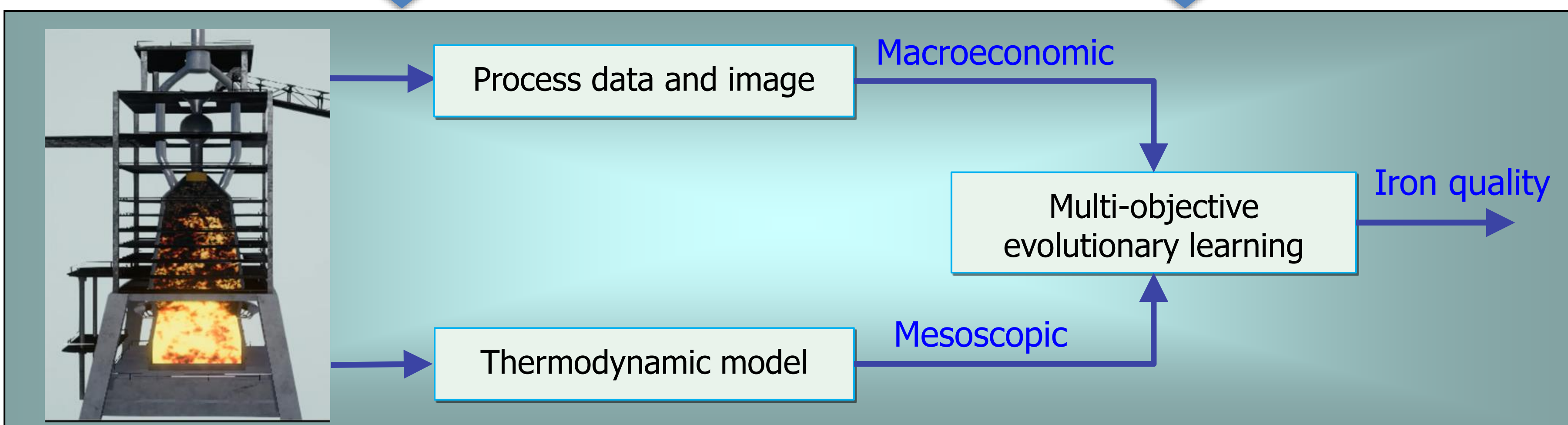
6. Data Analytics and Process Optimization for Quality

Case 1. Iron-making —— Iron Quality Prediction

Multi-objective Evolutionary Ensemble Learning

Fusion of thermodynamic model (meso) and process data (macro) ⇨ **Sub-learner based on fusion of meso and macro data**

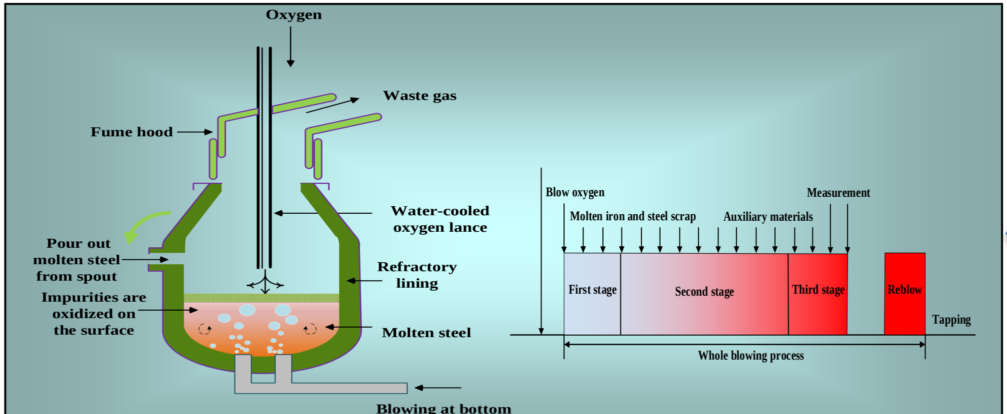
Multi-objective evolutionary algorithm ⇨ **Evolving the structure and parameters of ensemble model**



X. Wang, T. Hu, and L. Tang. A multiobjective evolutionary nonlinear ensemble learning with evolutionary feature selection for silicon prediction in blast furnace. ***IEEE Transactions on Neural Networks and Learning Systems***, 2021.

6. Data Analytics and Process Optimization for Quality

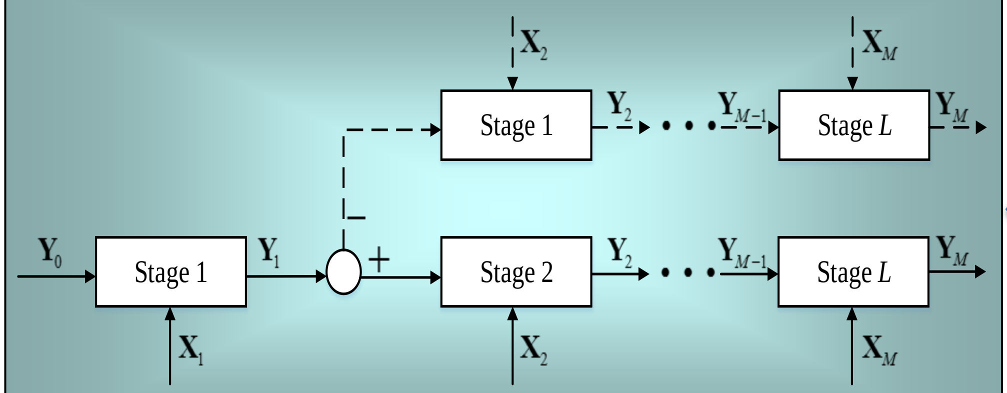
Case 2. Steelmaking —— Dynamic Prediction



Production process of BOF steelmaking

Challenges

- Continuous prediction requirement
- Unstable performance of single model
- Dynamic adjustment requirement



Principle of multi-stage modeling in BOF steelmaking process

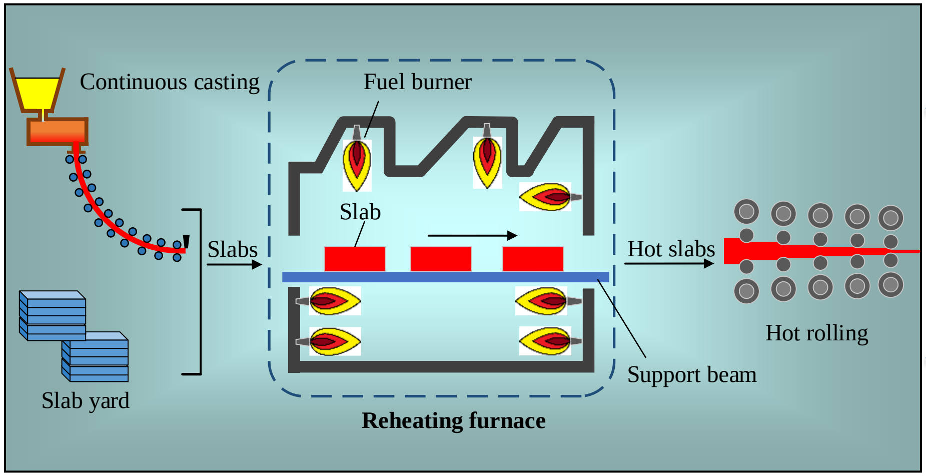
Dynamic analytics method

- Multi-stage modeling strategy
- Dynamic model with feedback
- Hybrid kernel function
- Differential evolution algorithm

C. Liu, L. Tang, J. Liu, Z. Tang. A dynamic analytics method based on multistage modeling for a BOF steelmaking process. *IEEE Transactions on Automation Science and Engineering*, 2019, 16(3): 1097-1109.

6. Data Analytics and Process Optimization for Quality

Case 3. Hot Rolling —— Temperature Prediction of Reheat Furnace

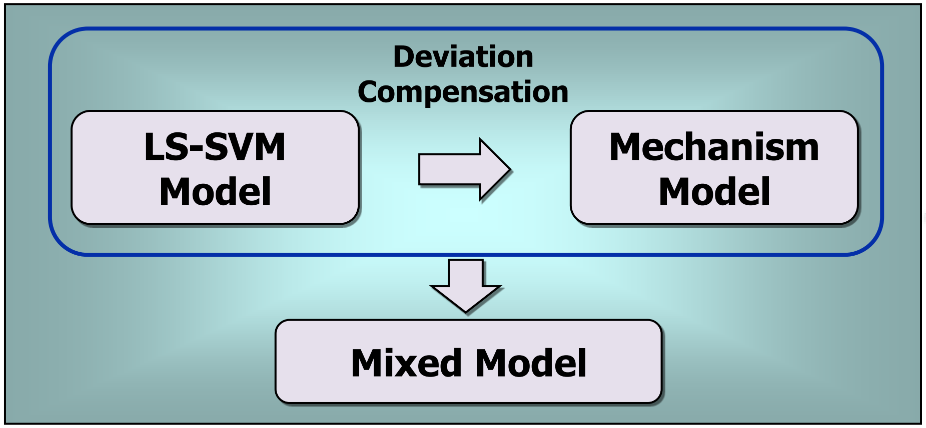


Features of Heating Process

- Dynamic
- Non-linear

Mechanism Model

- Difficult to obtain
- Obvious prediction error



Mechanism Model

- LS-SVM is used to compensate for the prediction deviation of the slab temperature
- Significantly improve the model prediction accuracy

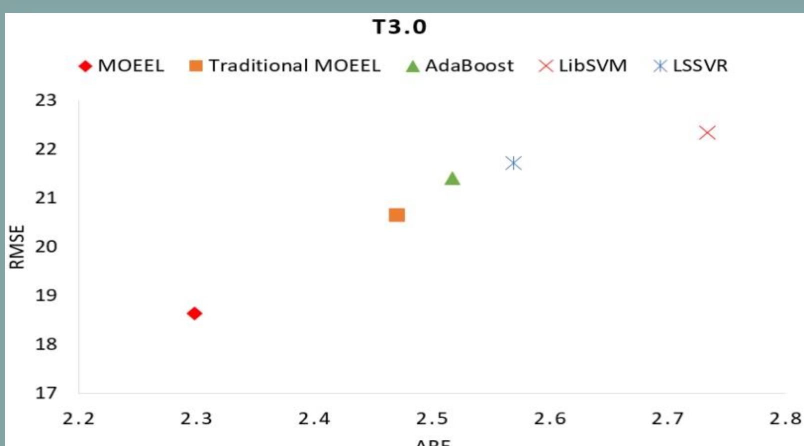
6. Data Analytics and Process Optimization for Quality

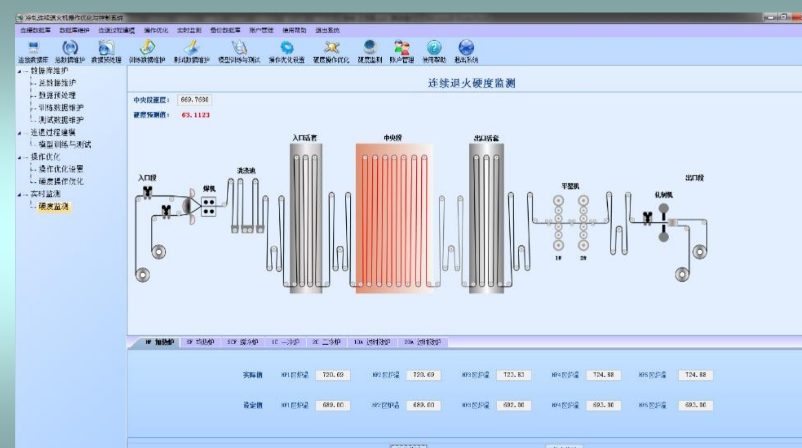
Case 4. Cold Rolling —— Strip Quality Analytics

Multi-objective Ensemble Learning

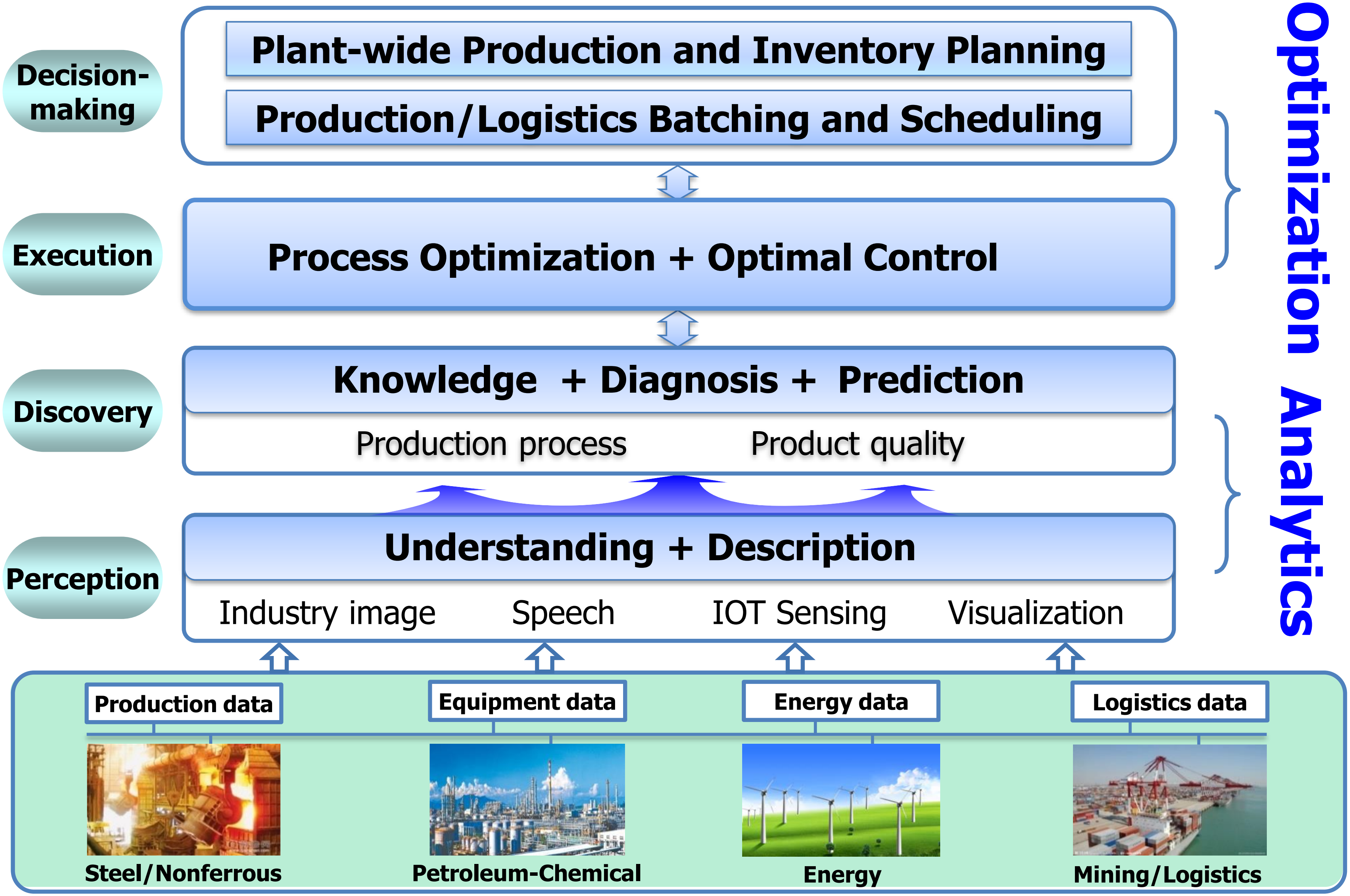
Least square support vector machine (LSSVM) ⇨ **Sub-learner in the ensemble learning**

Multi-objective evolutionary algorithm ⇨ **Evolving the ensemble learning model**





Conclusion and On-going Research



L. Tang, Y. Meng. Data analytics and optimization for smart industry. ***Frontiers of Engineering Management***, 2021, 8(2): 157-171.

Conclusion and On-going Research