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SURROGATE MODEL BASED OPTIMIZATION OF INDUSTRIAL COGENERATION SYSTEM UNDER REAL-TIME ENERGY COMMODITY MARKET

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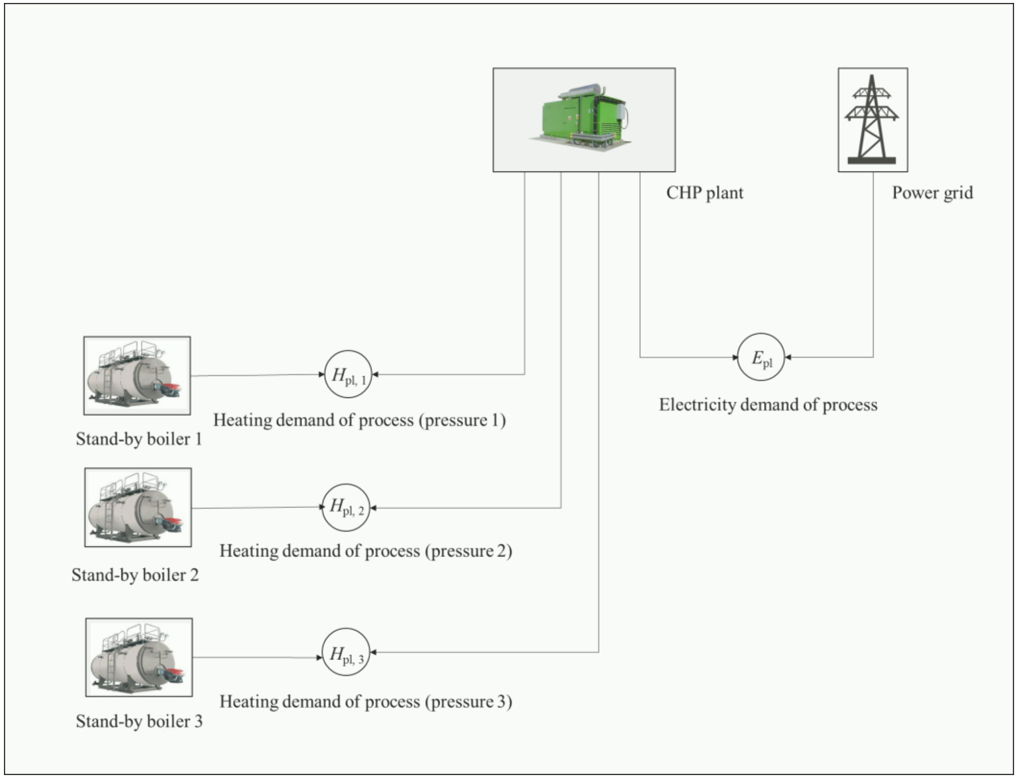
Outline

1. Background
2. Surrogate modeling techniques
3. Formulation of the optimization problem
4. Results and discussions
5. Conclusion

Industrial cogeneration system

- Utility system to serve industrial process power and heating demand
- CHP + stand-by boiler + power grid



Energy flows in cogeneration system:

Power flow:

1. CHP plant to industrial process;
2. CHP plant to power grid;
3. Power grid to industrial process.

Heat flow:

1. CHP plant to industrial process;
2. Boiler to industrial process.

Industrial cogeneration system research problems

Classical solutions:

- System design problem (optimal synthesis): what units to choose during design stage?
- System operation problem (optimal scheduling): how to run different units?

New challenges:

- The paradigm shift from equation based modelling to data driven modelling;

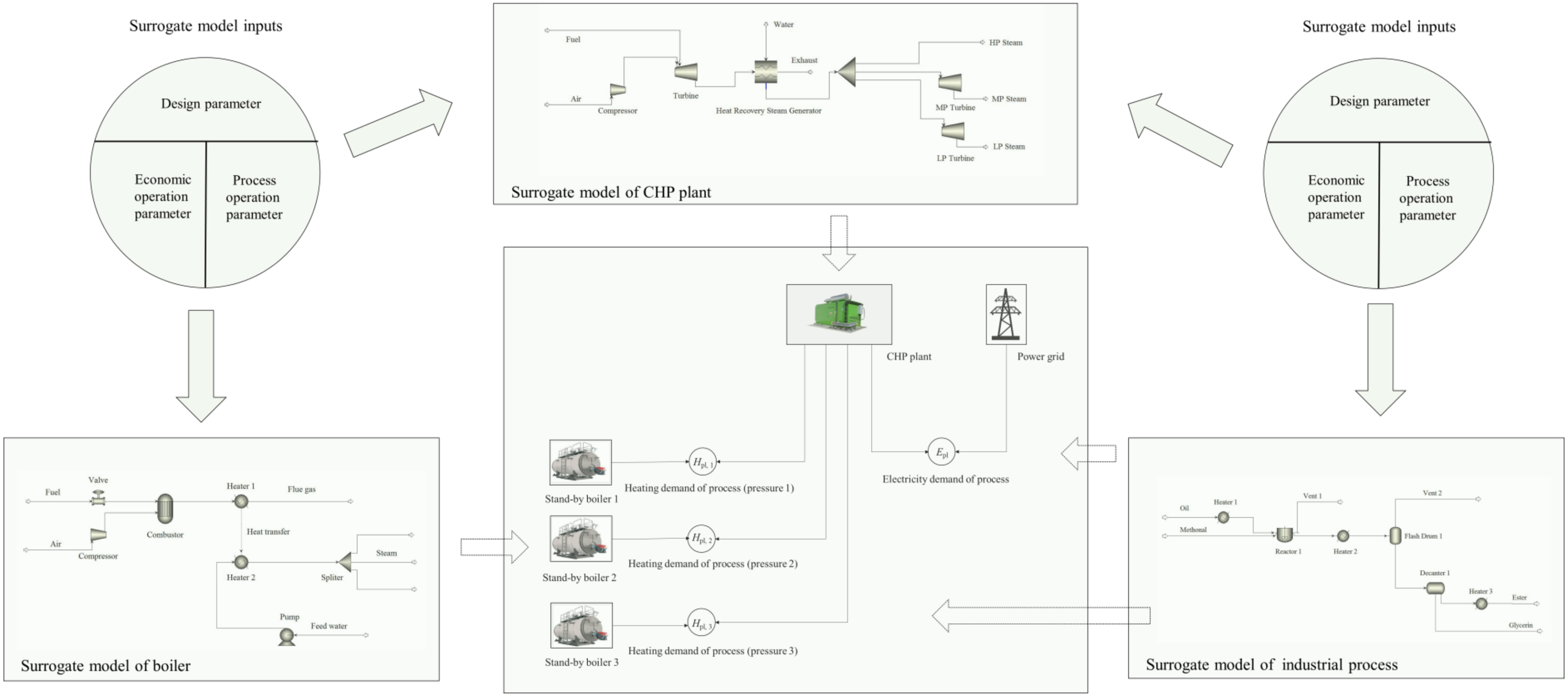
  Wealth of data in demand forecasting, operation unit commitment etc.
- The liberalization of energy commodity market;

  Time-sensitive electricity and nature gas price.
- Simultaneous process synthesis and utility system design.

  A generic framework to solve design and operation problem simultaneously.

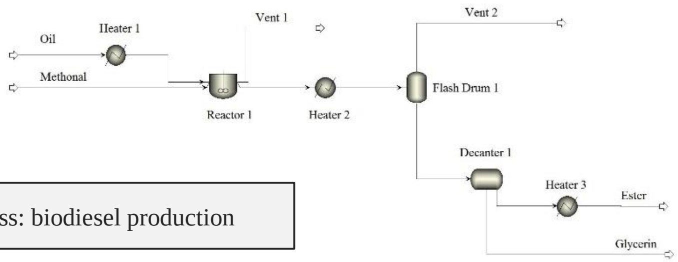
Necessity of a novel design and operational optimization methodology!

Surrogate model based optimization

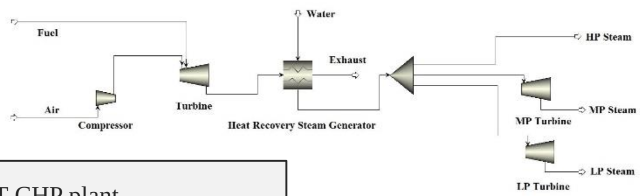


Schematic of surrogate model based optimization

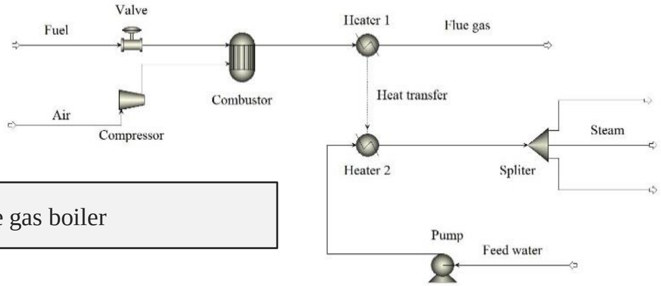
Surrogate model based optimization



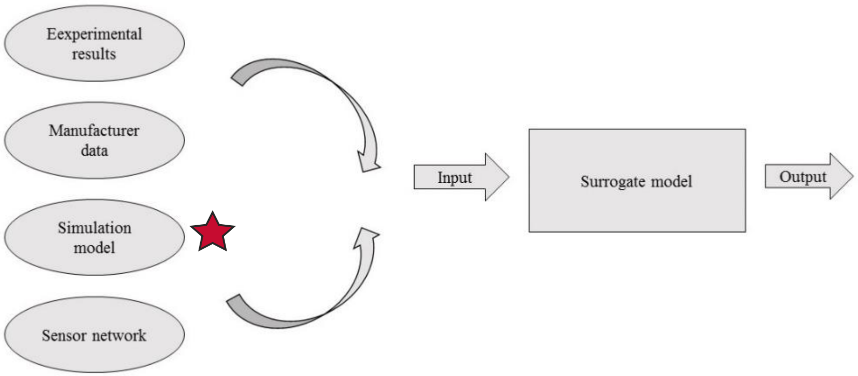
Industrial process: biodiesel production



CCGT CHP plant



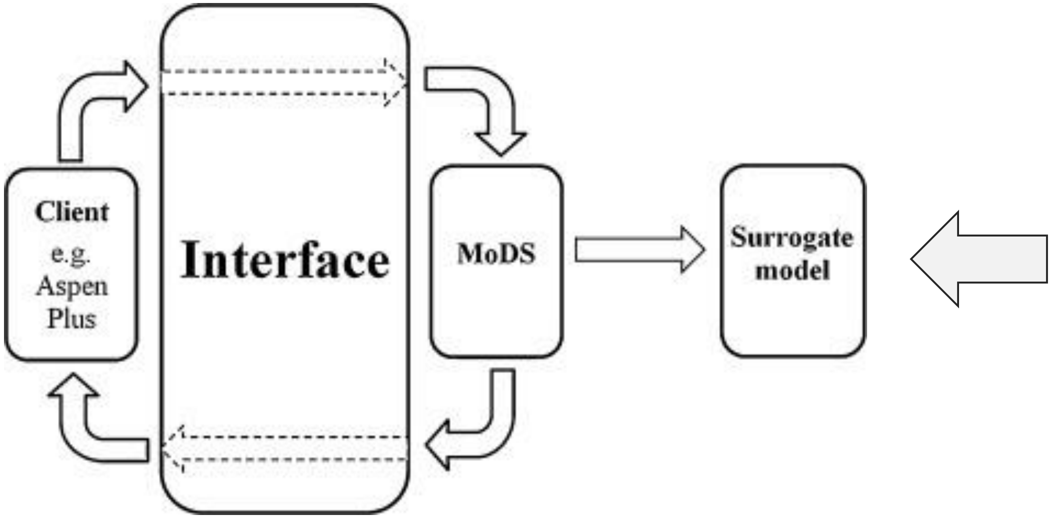
Nature gas boiler



Construction of surrogate model

Surrogate model based optimization

Model object	Model output	Model input	Model algorithm
CHP Plant	Power generation	Fuel flowrate, temperature, pressure	HDMR, ANN, SVM
	Steam generation	Fuel flowrate, temperature, pressure	HDMR, ANN, SVM
Boiler	Steam generation	Fuel flowrate, temperature, pressure	HDMR, ANN, SVM
Industrial Process	Process heat demand	Raw material flow rate, temperature, pressure	HDMR, ANN, SVM
	Process power demand	Raw material flow rate, temperature, pressure	HDMR, ANN, SVM



1. Iterative running Aspen plus within the design space to produce enough data points for surrogate model;
2. Prescribe aspen plus inputs and extract aspen plus outputs with python scripts.

Construction of surrogate model

Optimization problem formulation

Generic description:

What design variables $\mathbf{u_{des}}$, operation variables $\mathbf{u_{op}}$ and state variables $\mathbf{x}$ are considered in this paper?

$$\max_{\boldsymbol{x},\boldsymbol{u}_{des},\boldsymbol{u}_{op}} NPV(\boldsymbol{x},\boldsymbol{u}_{des},\boldsymbol{u}_{op})$$

$$\mathbf{u}_{des},\mathbf{u}_{op} \in \boldsymbol{\Omega}$$

$$g(\boldsymbol{x},\boldsymbol{u}_{des},\boldsymbol{u}_{op}) \leq 0$$

Maximize the NPV of cogeneration system under design variable $\mathbf{u_{des}}$, operation variable $\mathbf{u_{op}}$ and state variable $\mathbf{x}$

$s \in \mathbf{S} = \mathbf{C} \cup \mathbf{B} \cup \mathbf{I}$ ⇨ Set of CHP plant, boiler and industrial processes

$x_s, x_{s,t} \in \mathbf{x} = \{0,1\}$ ⇨ Binary variable for commitment state of component s during time period t

$c_s \in \mathbf{u}_{des}$ ⇨ Capacity of different components

$p_t^{el,sell}, p_t^{el,buy}, p_t^{gas,buy} \in \mathbf{u}_{op,econ} \subset \mathbf{u}_{op}$ ⇨ Price of natural gas buy, power buy and sell

$e_t^{sup,cog}, e_t^{sup,grid}, e_t^{dem}, h_t^{sup,cog}, h_t^{sup,boil}, h_t^{dem} \in \mathbf{u}_{op,proc} \subset \mathbf{u}_{op}$ ⇨ Energy flow amounts

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Optimization problem formulation

Objective function:

$$NPV(\boldsymbol{x}, \boldsymbol{u}_{des}, \boldsymbol{u}_{op}) = f \cdot AR - CPEX$$

$$NPV(\boldsymbol{x}, \boldsymbol{u}_{des}, \boldsymbol{u}_{op}) = f(i, CF) \cdot AR(\mathbf{x}, \mathbf{u}_{des}, \mathbf{u}_{op}) - CPEX(\mathbf{x}, \mathbf{u}_{des})$$

Present value factor

$$f(i, CF) = \frac{(i+1)^{CF} - 1}{i \cdot (i+1)^{CF}}$$

Annual Revenue

Initial Cost

$$AR(\mathbf{x}, \mathbf{u}_{des}, \mathbf{u}_{op}) = \sum_{t \in T} [\Delta t \cdot (p_t^{el,sell} \cdot e_t^{grid,sell} - p_t^{el,buy} \cdot e_t^{grid,buy} - p_t^{gas,buy} \cdot q_t^{gas,buy})] - \sum_{s \in \mathbf{S}} \sum_{t \in T} OPEX(\lambda, c_s, x_s, x_{s,t})$$

$$CPEX(\mathbf{x}, \mathbf{u}_{des}) = \sum_{s \in \mathbf{S}} CPEX(c_s, x_s)$$

NPV = Present value factor * Annual Revenue – Initial Cost

Optimization problem formulation

Constraints:

$$e_t^{dem} = e_t^{sup,cog} + e_t^{sup,grid}, \forall t \in T$$

$$h_t^{dem} = h_t^{sup,cog} + h_t^{sup,boil}, \forall t \in T$$

$$h_t^{sup,cog}, h_t^{sup,boil}, e_t^{sup,cog}, e_t^{sup,grid} \geq 0$$

$$e_t^{sup,cog} \geq \alpha_{e,cog}^{min} \cdot c_{cog}, \forall t \in T$$

$$e_t^{sup,cog} \leq c_{cog}, \forall t \in T$$

$$h_t^{sup,cog} \geq \alpha_{h,cog}^{min} \cdot c_{cog}, \forall t \in T$$

$$h_t^{sup,cog} \leq c_{cog}, \forall t \in T$$

$$h_t^{sup,boil} \geq \alpha_{h,boil}^{min} \cdot c_{boil}, \forall t \in T$$

$$h_t^{sup,boil} \leq c_{boil}, \forall t \in T$$

$$x_s \geq x_{s,t}, \forall t \in T, \forall s \in S$$

Energy balance constraints

Logic constraints

Optimization problem formulation

Where does the surrogate model feed into the framework?

$$AR(\mathbf{x}, \mathbf{u}_{des}, \mathbf{u}_{op}) = \sum_{t \in T} [\Delta t \cdot (p_t^{el,sell} \cdot e_t^{grid,sell} - p_t^{el,buy} \cdot e_t^{grid,buy} - p_t^{gas,buy} \cdot q_t^{gas,buy})] - \sum_{s \in \mathrm{S}} \sum_{t \in T} OPEX(\lambda, c_s, x_s, x_{s,t})$$

Objective function is about q gas, buy

$$h_t^{sup,cog} = sur_1(q_t^{gas,buy})$$

$$e_t^{sup,cog} = sur_2(q_t^{gas,buy})$$

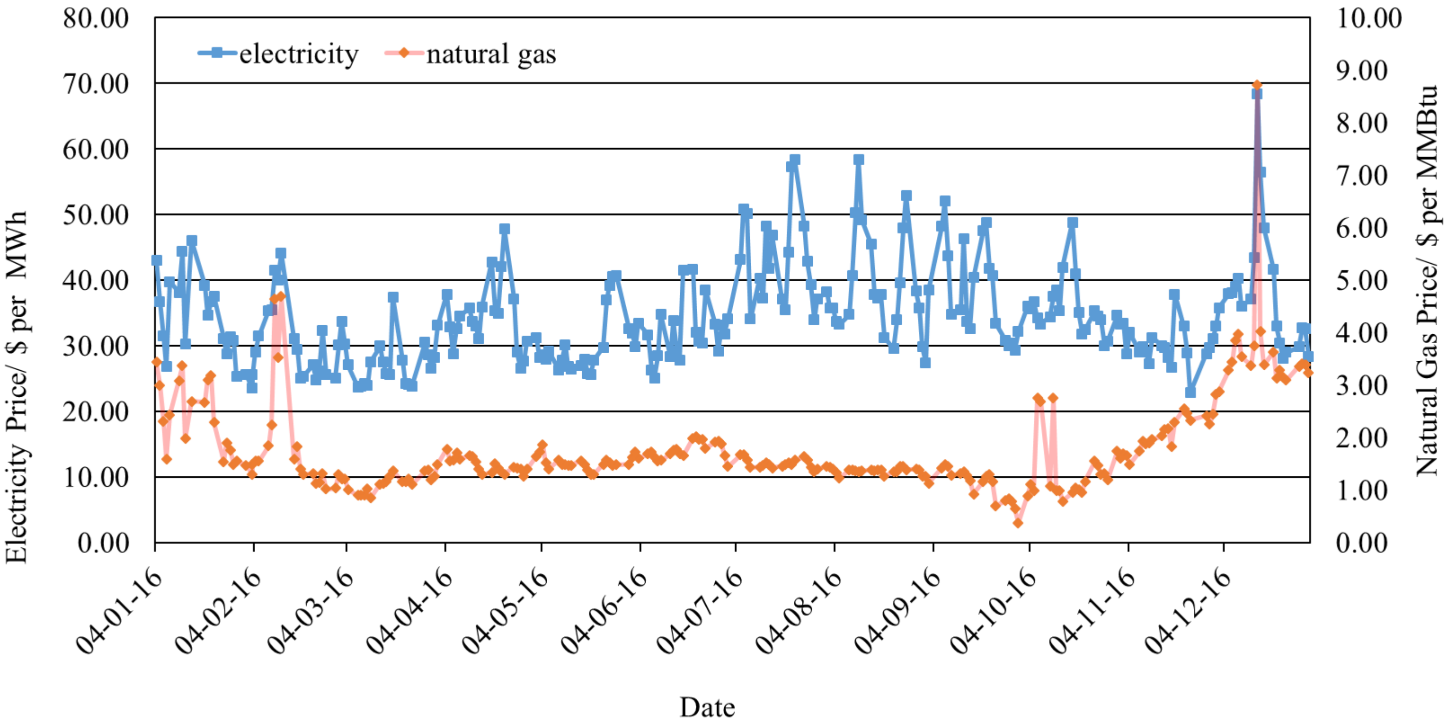
Surrogate model as bridge

$$e_t^{dem} = e_t^{sup,cog} + e_t^{sup,grid}, \forall t \in T$$

$$h_t^{dem} = h_t^{sup,cog} + h_t^{sup,boil}, \forall t \in T$$

Constrains are about h sup, cog and e sup, cog

Results and discussions



Electricity and natural gas price at PJM region in U.S. during 2016

Results and discussions

Equipment mix of the case study

One industrial process ***I***

*I*1: 80ton/h steam @ 21bar and 320^{o}C, 30 MW electricity demand

Two CHP units ***C***

C1: heat capacity 46ton/h steam, electricity capacity 25 MW;
C2: heat capacity 50ton/h steam, electricity capacity 30 MW.

Two boiler units ***B***

B1, B2: heat capacity 45ton/h steam .

Other assumptions

1. minimum partial load factors are 50%;
2. feed-in tariff equals to power price;
3. ***random fluctuation within the range of 10% of the flow rate of raw material streams in the industrial processes.***

⇩

Results in fluctuation of the demand profile!

Results and discussions

Three operation strategies:

Strategy 1

The surrogate model optimization resulted operation strategy

Strategy 2

Heat-lead strategy (e.g. strategy 2): Cogeneration plants supply as much heat as possible to fulfil the process heat demand while the boilers are used to supplement the deficits.

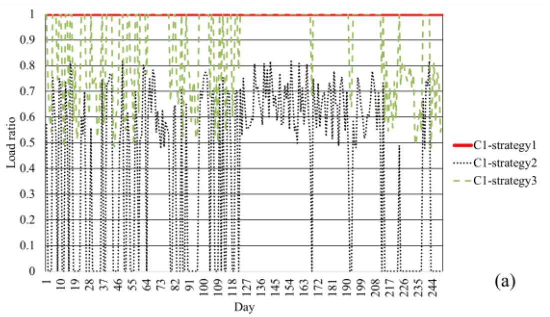
Strategy 3

Electricity-led strategy (e.g. strategy 3): Cogeneration plants supply as much electricity as possible to fulfil the process electricity demand while power import from grid is used as stand-by option.

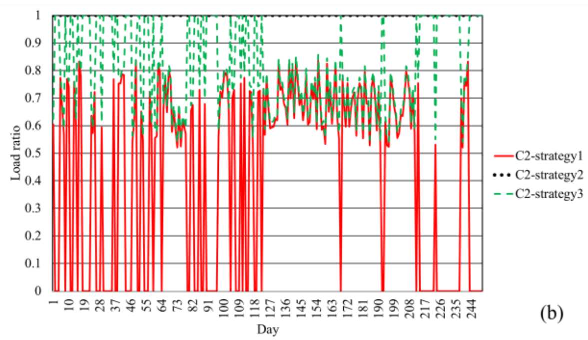
What units should be prioritized in design and operation stage resulted by three different strategies?

Results and discussions

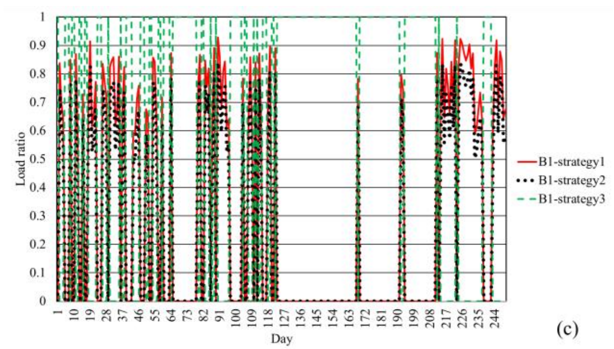
Unit commitment results



CHP unit C1



CHP unit C2

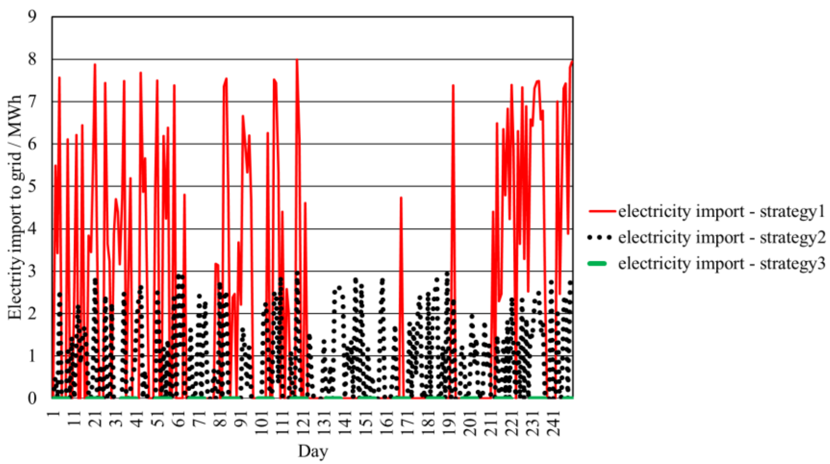


Boiler B1

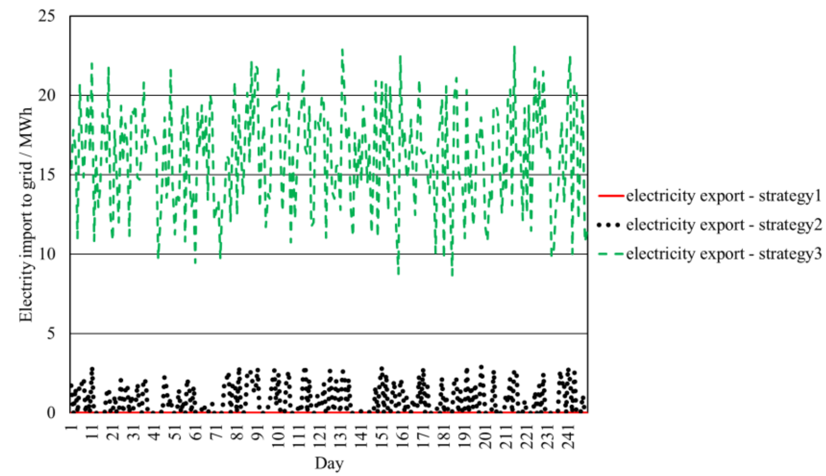
The surrogate model based optimization could result in frequent operation load switch

Results and discussions

Electricity import and export results



Electricity import



Electricity export

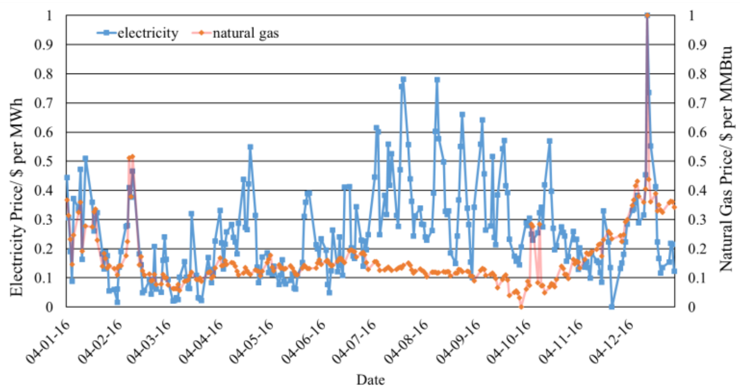
Strategy 1 prefers to export power to grid at almost the whole operational period during the year.

Cost of generating electricity from cogeneration plant is always lower than the cost of importing electricity from grid.

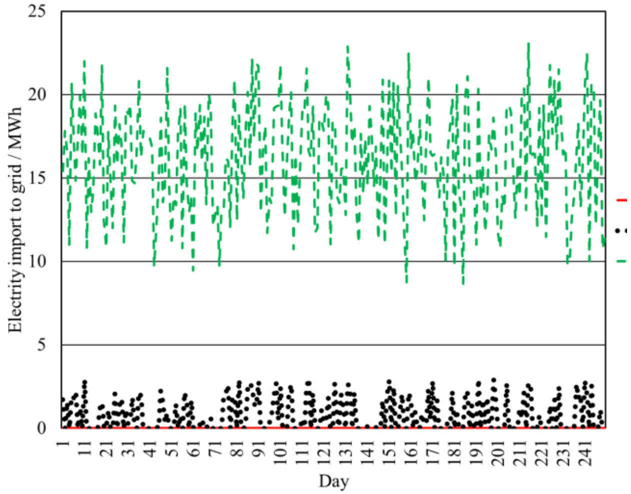
Results and discussions

Covariance between feed-in electricity amount and power price

Pearson correlation coefficient is about 0.8 (highly correlated)



Normalized energy price



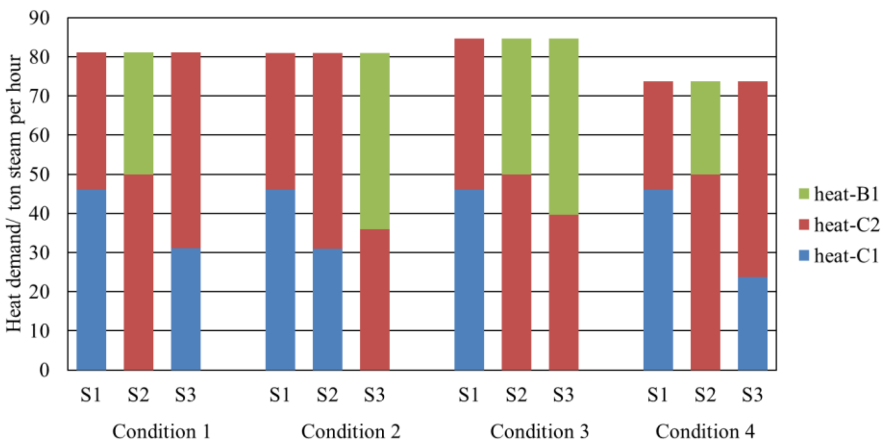
Electricity export

The proposed methodology is able to capture the inherent economics of balancing industrial process demand and electricity generation!

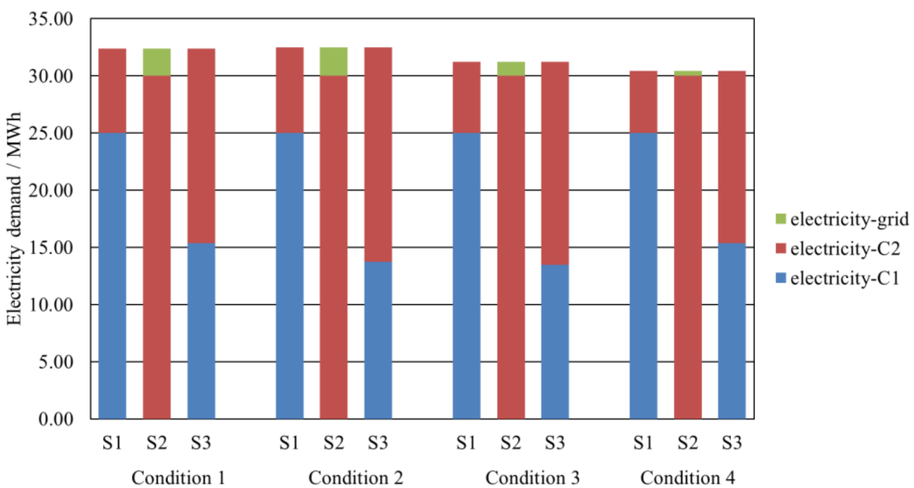
Results and discussions

Heat profile and electricity profile breakdown under four typical conditions

S1: heat-lead strategy; S2: the electricity-led strategy; S3: surrogate model optimization strategy.



Heat profile



Power profile

Condition 1: both electricity price and natural gas price are high;
Condition 2: both electricity price and natural gas price are low;
Condition 3: electricity price is high whereas natural gas price is low;
Condition 4: electricity price is low whereas natural gas price is high.

Conclusions

1. Surrogate model based optimization framework is an efficient formulation to solve the optimization problem of industrial cogeneration system.

2. Surrogate model based approach could dynamically react to the heating and electricity demand profile change induced by operation parameter change. This is an important feature of the proposed approach because it harbors the potential of Model Predictive Control (MPC) of the cogeneration system.

3. The surrogate model optimization resulted operation strategy is proven to be superior to the conventional heat-led or electricity-led operation strategy. Around 10% total annual cost can be reduced if the proposed surrogate model based optimization framework is used compared to traditional heat-led or electricity-led operation strategy.

4. Consideration of time-sensitive electricity and commodity price in real-time energy market is critical in the optimization of CHP plant. Compared to the scenario where electricity and natural gas price is constant, optimization with time-sensitive electricity and commodity price can save up to 18% of utility fee per year.

Thanks and questions?



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