

Load Optimisation of Multiple Boiler System (MBS) via P-graph

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Multiple boiler system (MBS) is commonly applied in the industry to cater to the process steam demand reliably and flexibly. Optimising load allocation among the boilers is significant for the routine boiler system efficiency and carbon emission reduction. This aligns with the objective of "RENKEI control" to achieve the optimum cooperative energy efficiency between multiple elements that interact with one another. MBS can be implemented in a centralised or decentralised manner, depending on the unit allocation and process extension planning. Generally, the boiler load allocation is optimized via the complex engineering mathematic approach or modelling, which might not be user-friendly for the in-house engineer without sound mathematical knowledge and optimization background. Therefore, a user-friendly tool and method to handle problems of high combinatorial complexity with a low computational burden are needed. In this paper, the graph theoretic tool, Process Graph (P-graph), which was initially used for Process Network Synthesis (PNS), is applied to optimize the load allocation of both centralised and decentralised MBS considering the non-linear boiler part-load efficiency and existing steam piping network constraint. Besides, the fuel consumption by the existing on-site boiler operation strategy, such as parallel, tandem, and user-assigned mode, can be checked by simply modifying the P-graph structure to identify the potential improvement of MBS load optimization. The methodology proposed achieves 2.48 % and 2.37 % fuel savings in both centralised and decentralised MBS optimisation. Former case demonstrates a similar result (different by 0.02 %) compared to other authors' work.

1. Introduction

The Japanese word "RENKEI" is described as "cooperation or coordination". "RENKEI control" is the initiative to optimise energy efficiency between two or more elements interacting with each other (JEITA and GIPC, 2012). Optimum load allocation of multiple boiler systems (MBS) is one of the "RENKEI control" strategies among the same equipment within an energy supply facility (Ikeyama and Sueyoshi, 2021).

Dunn and Du (2009) proposed the second-order gradient search method to allocate the load of multiple boilers optimally considering multiple fuel types. Ma et al. (2015) applied the decomposition and coordination method to optimise MBS operation in an integrated steelwork plant. In addition, Polinelli (2018) used MATLAB software to check the performance and feasibility of the MBS load optimisation task at an Alumina refinery plant by inputting different constraints. Wan et al. (2022) applied genetic algorithm to optimise the load distribution of turbines and multiple boilers to minimize the coal consumption. The earlier two methods involve a Lagrangian-based approach that requires users to have higher complexity of the mathematical background. In contrast, the latter method requires users to have technical skills to write the coding of particular software. A user-friendly tool and method to handle problems of high combinatorial complexity and low computational burden is needed. The P-graph framework is a combinatorial approach to synthesise and optimise process networks. Its simple interface showcases high efficiency in tackling problems of high combinatorial complexity with a low computational burden. It is proven to solve various engineering applications, including sustainable heat and electricity supply system with flexible input ratios (Éles et al., 2020) as well as synthesis of cogeneration system considering error tolerances (Lin et al., 2022). In addition, non-linearity characteristic was introduced into the P-graph by using the approximate linearisation method (Ong et al., 2016) and artificial neural networks (ANN) (How et al., 2019). However, scarce study is reported to explore the P-graph application in the MBS load optimisation, considering both non-linear boiler part-load efficiency, multiple fuels selection, and existing steam

pipng network constraints. This paper aimed to bridge the gap by providing alternatives and guidelines to optimise load allocation of MBS via P-graph. Two types of MBS – centralised and decentralised MBS are demonstrated to show P-graph's flexibility in solving the boiler load optimisation problem. The ability of the P-graph to check the MBS performance at different boiler operating strategies is explored to identify the potential improvement after implementing MBS load optimisation.

2. Methodology

The P-graph software is available online, free to download and apply. The P-graph is a bipartite graph with nodes under the M-type (materials) or O-type (operations) categories. In conventional PNS, inputs and outputs are represented by M-type nodes and connected to the process operation unit signified by O-type nodes. The input-output ratio, such as the stoichiometry of reaction or thermodynamics relationship, needs to be inputted into P-graph (Friedler et al., 1992). P-graph will generate the optimal and near-optimal solutions via the Accelerated Branch-and-Bound (ABB) algorithm.

This section presents four procedures to construct the MBS in the P-graph with the objective function to minimize the operating expenditure, OPEX of MBS via the optimization of boiler load allocations among multiple boilers, as shown in Eq.1. OPEX of MBS here covers only fuel cost which consists of two elements – cost of energy of steam, CE_o and cost of energy penalty due to boiler efficiency loss, CE_p . Different boilers have different boiler efficiency curves for their part-load condition. In P-graph, the optimum load allocation among MBS is identified to minimize CE_p and OPEX in catering the targeted steam demand.

$$\text{Objective function} = \text{Min OPEX} = \text{Min} \sum (CE_o + CE_p) \quad (1)$$

Step 1: Data collection

Prices of fuels applied per unit of energy, C_F , allowable operating range of boilers and part-load efficiency of the boilers, η (%) based on data from boiler suppliers or historical performance need to be prepared by the users.

Step 2: Convert the boiler efficiency curve into cost of energy penalty curve

The boiler efficiency, η curve against part-loads, i of each boiler, j is converted into cost of energy penalty, $CE_{p,ij}$ curve based on Eq.2. $S_{d,ij}$ is the steam demand that catered by particular boiler while $H_{\text{conversion}}$ is the enthalpy difference between the BFW and steam produced per 1 t of steam.

$$CE_{p,ij} = S_{d,ij} \times H_{\text{conversion}} \times \left(\frac{100}{\eta_{ij}} - 1 \right) \times C_{F,j} \quad (2)$$

Cost of energy of steam, $CE_{o,ij}$ is the enthalpy difference between the BFW and steam produced, which will be calculated automatically by the P-graph after keying in information stated in Step 4. $CE_{o,ij}$ is calculated based on Eq.3.

$$CE_{o,ij} = S_{d,ij} \times H_{\text{conversion}} \times C_{F,j} \quad (3)$$

Step 3: Linearise the cost of energy penalty curve within the tolerable error

Each boiler's cost of energy penalty curve is divided into multiple subintervals to form the approximated piecewise linearised equation (Ong et al., 2016). This is important as the P-graph only accepts the fixed and proportional operating cost in linear form. The error between the non-linear curve and each interval's linearised equation can be calculated using Eq.4. Users can determine the tolerable error and modify the number of subintervals to achieve the tolerable error. Step 2 and 3 are illustrated in Figure 1.

$$\text{Error} = \frac{CE_{p,ij \text{ curve}} - CE_{p,ij \text{ linear}}}{CE_{p,ij \text{ curve}}} \times 100 \% \quad (4)$$

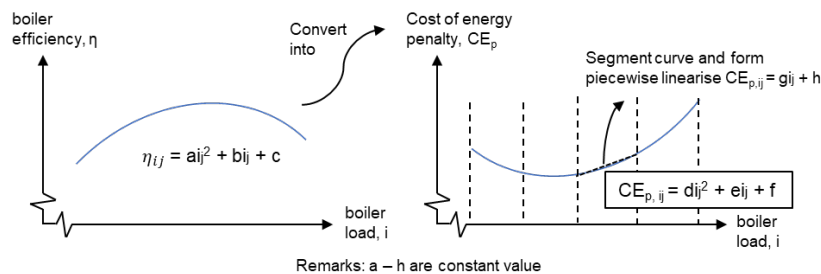


Figure 1 Graphical representation of converting the boiler efficiency curve into cost of energy penalty curve

Step 4: Construct the MBS in P-graph

The MBS considering part-load efficiency comprises of five fundamental elements in P-graph – fuels, boilers, fictitious boilers operating at different loads and efficiency, headers, and steam. The maximal superstructure of a boiler is presented via the P-graph in Figure 2. Few numbers of similar boiler superstructures form the MBS.

Step 5: Connect the steam generated by each boiler in P-graph based on the boiler operation strategies
 First, users have to input fuel price $C_{F,j}$ of each boiler into the fuel node, piecewise and linearised cost of energy penalty, $CE_{p,ij}$ equations into the fictitious boilers nodes and process steam demand required, $S_{d,targeted}$ into the final steam demand node. This input actions are represented by the red colour arrows in Figure 2.

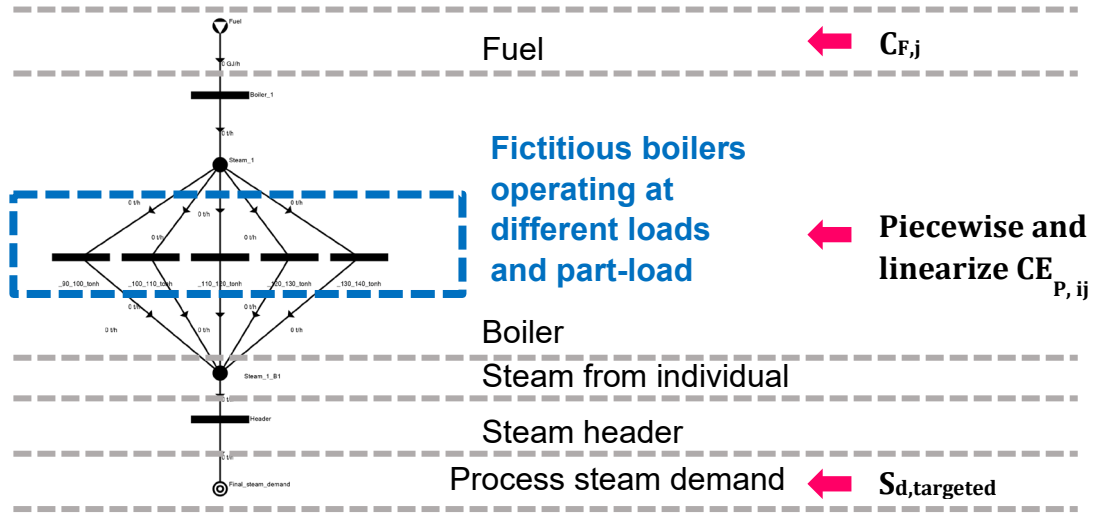


Figure 2: Maximal superstructure of a boiler via P-graph with input data

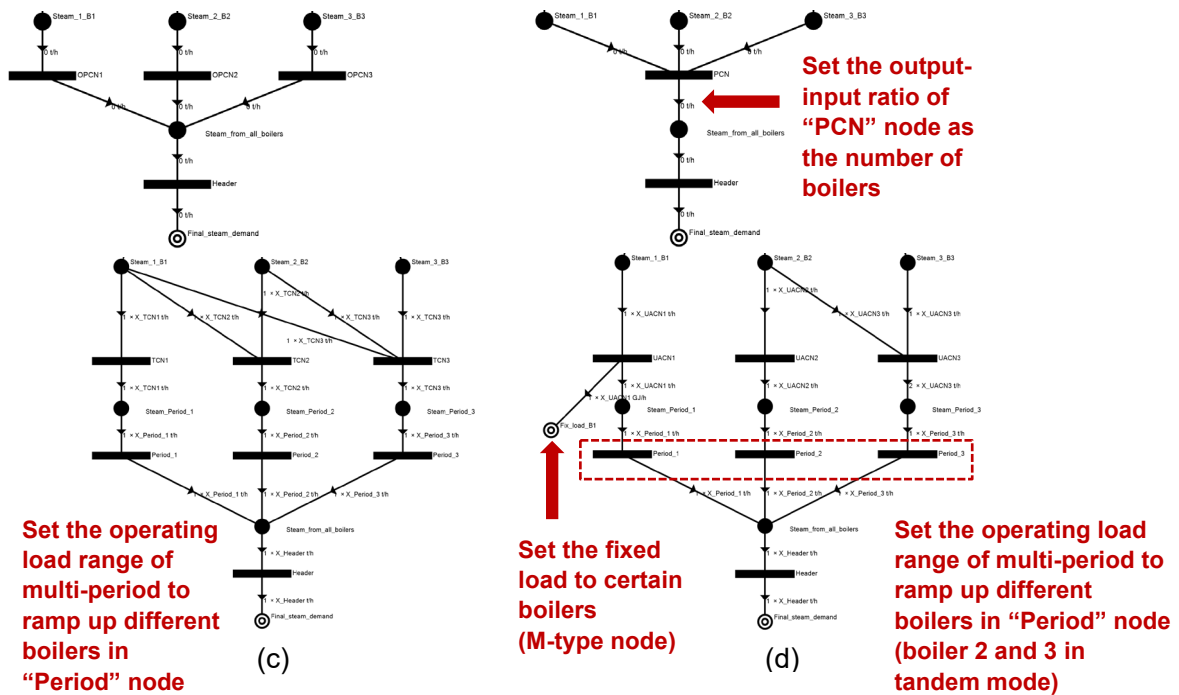


Figure 3: Connection (CN) of steams of each boiler for different types of operating strategies – (a) Optimised mode (OPCN), (b) parallel mode (PCN), tandem mode (TCN) and (d) user-assigned mode (UACN)

Secondly, users must connect the steam from individual boiler based on the selected operating strategies, as shown in Figure 3. There are numerous MBS operation strategies to supply the process steam demand, namely load-optimised, parallel, tandem, and user-assigned operation mode. Different boiler operation strategies apply different architectures of the P-graph. The operating principles of different modes are described as follows.

- i. Optimised mode – The boiler loads are optimised considering their part-load efficiency. In the P-graph, all steam produced by each boiler is connected to the header via the “OPCN” node to generate the most efficient MBS operation solution.
- ii. Parallel mode – All boilers share the load equally. In the P-graph, the output-input ratio of steam entering the “PCN” node is set based on the number of on-site boilers.
- iii. Tandem mode – The most efficient boiler is selected as the lead boiler, while the remaining boilers act as the lag boilers. The lead boiler will ramp up till the maximum allowable operating load, followed by the ramp-up of the first lag boiler to share the loads equally. After achieving the maximum allowable operating load, this cycle repeats for the subsequent lag boilers. In the P-graph, the “TCN” and “Period” nodes are added to set the sequence and operating load range of the multi-period to ramp up boilers in different steam demands.
- iv. User-assigned mode – The operator sets the boiler loads based on their experience with the performances of each boiler. Some of the boilers might be operated at fixed load while the remaining be operated at parallel or tandem mode to cater to the fluctuation of process steam demand. In the P-graph, the fictitious M-type node is added to fix certain boilers’ load.

3. Results and discussion

The case study of the MBS load optimization from the work of Dunn and Du (2009) is selected to validate the performance of the P-graph in allocating the boiler load optimally and minimizing the OPEX of MBS. The boiler part-load efficiency and fuel price are tabulated in Table 1. There are five boilers on-site to meet the process steam demand. The $H_{\text{conversion}}$ of steam is 2.8115 GJ/t. In this paper, each boiler's maximum rated capacity is assumed to be 150.0 t/h, with a turn-down ratio of 0.40. However, for safety and controlling purposes, the maximum allowable operating load of boilers is limited to 140.0 t/h.

Table 1: Part-load efficiency curve and fuel price of different boilers

Boiler, j	Efficiency, η curve	R of curve	Fuel price, C_F (\$/GJ)	Site (decentralised case study)
1	$\eta_1 = -0.0075i_1^2 + 1.7204i_1 - 11.413$	1.00	4.231	2
2	$\eta_2 = -0.0062i_2^2 + 1.3013i_2 + 21.496$	1.00	4.231	3
3	$\eta_3 = -0.0001i_3^2 + 0.0328i_3 + 89.128$	1.00	5.284	2
4	$\eta_4 = -0.0053i_4^2 + 0.9928i_4 + 32.960$	1.00	4.155	1
5	$\eta_5 = -0.0052i_5^2 + 1.0608i_5 + 25.606$	1.00	4.648	2

3.1 Centralised MBS

In the centralised MBS, all boilers are located at one site only. All the steam consumers receive the steam from the same header. P-graph is applied to identify the optimum load allocation among five boilers to meet the process steam demand, 587 t/h during the normal plant operation period. Its maximal superstructure is displayed in Figure 4. Besides, the optimum operation cost of MBS at different load profiles are identified, considering abnormal operation periods such as shortage of raw material, high and low product demand in the market. In the tandem mode, sequence of ramping up boiler is set as boiler 4 \rightarrow 1 \rightarrow 3 \rightarrow 5 \rightarrow 2. In the user-assigned mode, output of boiler 4 is fixed at 140 t/h and remaining boiler is set at tandem mode (1 \rightarrow 3 \rightarrow 5 \rightarrow 2). The results are tabulated in Table 2. The optimised mode of MBS is the boiler operating strategy with minimum OPEX for different steam demand requirements. The result obtained from P-graph is compared with the boiler load allocation obtained in the works of Dunn and Du (2009) in Table 4, showing that the fuel costing recalculated based on Equation 1 - 3 is different by 0.02 % only. This validates that the P-graph can be used to optimise boiler load allocations considering part-load efficiency and types of fuel in high accuracy.

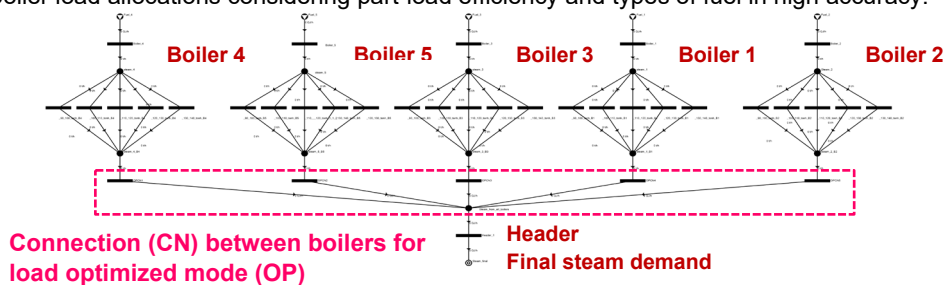


Figure 4: Maximal superstructure of centralized MBS for load optimization case to supply 587 t/h steam

Table 2: Operation cost of different MBS operation strategies at different boiler load profiles

Boiler load profile (%)	Boiler load (t/h)	Selected boilers to supply steam			OPEX of MBS (\$/h)				
		Optimised	Parallel	Tandem	User- assigned	Optimised	Parallel	Tandem	User- assigned
40.0	306.6	1, 2, 4	All	4, 1, 3	4, 1, 3	4,240.0	5,142.3	4,582.6	5,000.6
60.0	459.9	1, 2, 3, 4	All	4, 1, 3, 5	4, 1, 3, 5	6,673.4	6,912.4	7,083.6	7,348.3
76.6	587.0	1, 2, 3, 4, 5	All	4, 1, 3, 5, 2	4, 1, 3, 5, 2	8,750.2	8,826.4	8,826.4	9,069.5
90.0	689.9	1, 2, 3, 4, 5	All	4, 1, 3, 5, 2	4, 1, 3, 5, 2	10,960.5	10,989.8	10,989.7	11,010.8

3.2 Decentralised MBS

The decentralised MBS system with steam pipeline network is demonstrated in Figure 5. This case study is proposed to assess impact of existing steam pipeline network on boiler load optimisation. Process steam demand of each site consumer, C is tabulated in Table 3. Its maximal superstructure is showed in Figure 6.

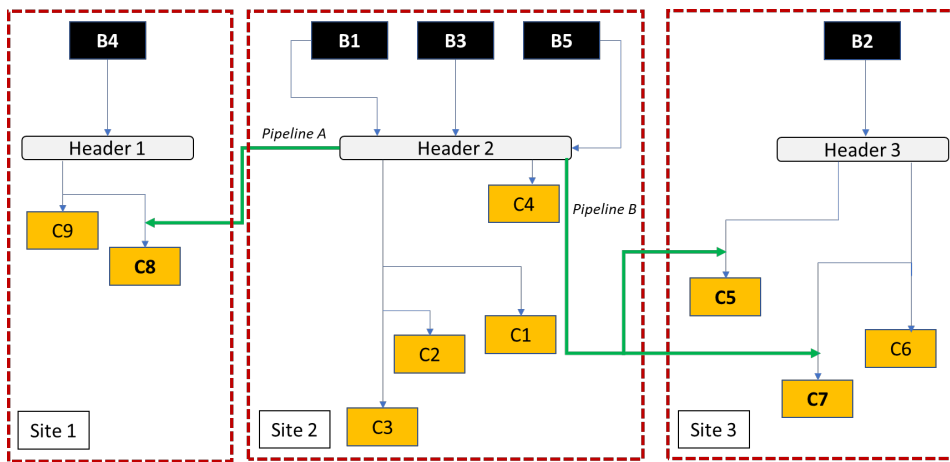


Figure 5: Decentralized MBS

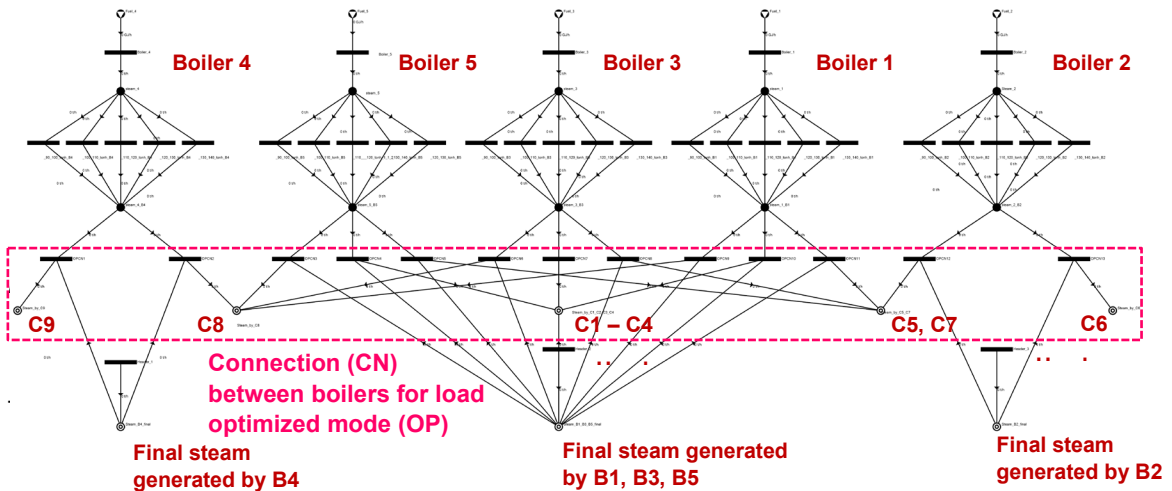


Figure 6: Maximal superstructure of decentralized MBS for load optimization case to supply 587 t/h steam

The operation cost of decentralised MBS is lower by 0.11 % compared with the centralised MBS, as tabulated in Table 4. This is because the steam consumption by consumers, C6 and C9 must be supplied by boiler 2 at site 3 and boiler 4 at site 1 based on the existing steam piping network. The minimum operating load of boilers 2 and 4 are limited by their on-site steam load, which cannot be supplied from boilers at site 2. The methodology proposed achieves fuel savings of 2.48 % and 2.37 % in both centralised and decentralised MBS optimisation compared to the original boiler loads allocation scenario.

Table 3: Process steam demand by each consumer

Site	Site 1	Site 2	Site 3
Steam consumption (t/h)	C8 – 70, C9 – 110	C1 to C4 – 247	C5 – 50, C6 – 80, C7 – 30
Total (t/h)	180	247	160

Table 4: Load optimization of centralized and decentralized MBS via P-graph to supply 587 t/h steam

Boiler	Boiler load (t/h)			
	Original	Work of Dunn and Du (2009)	This work – Centralized	This work – Decentralized
1	108.00	123.64	127.00	120.00
2	110.00	119.67	120.00	120.00
3	117.00	137.46	140.00	137.00
4	125.00	102.77	100.00	110.00
5	127.00	103.45	100.00	100.00
OPEX (\$/h)	8,973.0	8,748.4	8,750.2	8,760.0

4. Conclusions

A user-friendly methodology to optimise load allocation of MBS via P-graph has been developed in this study. The study incorporates different boiler operating strategies and constraints, such as existing pipeline networks in decentralised MBS. In the future, the load optimisation of MBS can be extended to consider applying different steam pressure levels and integrating solar thermal energy to reduce the carbon footprint further.

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