Performance of Centralised Trigeneration Plant on Sensitivity Analysis of Total Site System

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Abstract. The progressive rising of high living standards and populations’ growth has led to increasing energy demands. This has led to the energy shortage gap in both developing and developed countries. Government is developing new technology to increase the thermal efficiency of existing power systems. Trigeneration is one of the innovations that can increase the performance of power systems by reusing waste energy for heating and cooling applications. Pinch Analysis (PA) is a methodology that has been commonly applied for more than 40 years to design and optimum configurations of various resource networks. Previous studies have been performed optimisation of trigeneration system in a Total Site system based on the PA method called Trigeneration System Cascade Analysis (TriGenSCA). However, the previous study does not consider the performance of the trigeneration system through overall sensitivity analysis of Total Site system. Overall sensitivity analysis of the Total Site system that includes industrial plant's maintenance shutdown and production changes affected the performance of the centralized trigeneration system to generate energy to be supplied to the demands. Through this analysis, the size of the trigeneration system and back-up system can be estimated taking into consideration data fluctuations probability. The methodology has been tested on the centralized nuclear trigeneration system in a Total Site system considering four industrial plants as a case study, leading to extra 3.1 MW of Low-Pressure Steam (LPS) and 7.15 MW of Hot Water (HW) are needed from the back-up system if Plant B is shut down as well as extra of 82.4 MW of HW is needed by the back-up system if Plant C is shut down. The size of the boiler and condensate system, hence, need to be improved to overcome the deficit energy as the Plants B and C are shut down.

1. Introduction
The progressive rising of high living standards and populations’ growth has led to increasing energy demands. The energy demands in South East Asia is expected to be gradually increased from 244 Mt of oil equivalent (Mtoe) in 2018 to 329 Mtoe in 2040 [1]. The government is enhancing new technologies so that energy supplies can meet the rising of energy demands as well as reducing carbon emissions. The trigeneration system is a device that can provide power, heating and cooling energy from the same
burning process. The thermal efficiency of the established conventional power plant can be increased from 30–40% to 80–90% by the use of the trigeneration system [2]. Improvement of thermal efficiency can reduce fossil fuel resources and carbon emissions [3].

Pinch Analysis (PA) is a methodology that has been commonly applied for more than 40 years to design and optimum configurations of various resource networks. The PA methodology has been gradually growing in various resource networks such as heat [4], water [5], carbon emissions [6], mass [7] and power [8]. This shows that the PA methodology has received acceptance from the public. Jamaluddin et al. [9] has developed a method, namely the Trigeneration System Cascade Analysis (TriGenSCA) to optimise the trigeneration plant in a Total Site system. The recent study has also been done by Zhang et al. [10] to evaluate the feasibility of the trigeneration system by using mathematical model. However, the previous study does not consider the performance of the trigeneration system through overall sensitivity analysis of Total Site system. Liew et al. [11] developed a total sensitivity analysis of the Total Site system that includes an industrial plant's maintenance shutdown and production changes. But the total sensitivity analysis of the Total Site system can also affect the performance of the centralized trigeneration system to generate energy to the demands. This study extends a new contribution which is called as Trigeneration System Sensitivity Table (TriGenSST) to determine the impact of plants are shut down or production changes on the centralized trigeneration system and Total Site system. This feature is vital to allow energy managers and engineers to access the impact of sensitivity changes on the centralized trigeneration system.

2. Methodology and Case Study

This work extended the TriGenSCA methodology developed by Jamaluddin et al. [9] which includes the sensitivity analysis to determine the impact of industrial plants are shut down or production changes on the centralized trigeneration system and Total Site system. To demonstrate the extended TriGenSCA methodology, an illustrative case study for a centralized trigeneration system with four industrial plants that can exchange heat indirectly through Total Site system is used. In the Total Site system, excess heat is exchanged between industrial plants indirectly. If the industrial plants are still in deficit heat, the centralized trigeneration system will provide power, heating and cooling to the Total Site system. A boiler from the centralized trigeneration system produces Very High Pressure Steam (VHPS) and after that, supplies the double extraction steam turbine for power generation, High Pressure Steam (HPS) and Low Pressure Steam (LPS). Then, lower pressure steam is condensed in the condenser to produce Hot Water (HW) or directly supplied to the demands. The HW is used to supply directly to the demands or cooled further to produce Cooling Water (CW) by using cooling tower and Chilled Water (ChW) by using absorption chiller. Figure 1 shows integration of the centralized trigeneration system with the Total Site system.

The procedure of this methodology is presented in seven steps: extraction of data, identification of time pieces, Problem Table Algorithm (PTA), Multiple Utility Problem Table Algorithm (MU PTA), Total Site Problem Table Algorithm (TS PTA), TriGenSCA, and TriGenSST. Energy source and demand data are required to be obtained as a first step in the TriGenSCA's extended methodology. Tables 1 to 4 show the hot and cold demand streams for industrial plants, namely Plants A, B, C and D in time slices which are obtained and modified from Perry et al. [12]. Multiple utility level temperatures are shown in Table 5 and will be used in MU PTA. The hourly power data of Plants A to D are obtained directly from literature reviews and shown in Figure 2. The centralized trigeneration system as an energy source, on the other hand, is assumed to be operated based on the average power demands. The trigeneration system needs to produce 612 MW of power to the demands. The boiler needed 2,040 MWth to produce 612 MW of power from the double extraction steam turbine with consideration of 30% efficiency. Another 1,428 MW of waste heat are assumed to operate in (1) 16.65 MW of HPS, (2) 290.45 MW of LPS, (3) 303.48 MW of HW, (4) 200 MW of CW, (5) 40 MW of ChW and (6) 577.42 MW or translating into 28% of total energy are losses.
Figure 1. Illustrative design of a centralized trigeneration system with Total Site system [9]

Figure 2. Electricity consumption on each industrial plants [13, 14, 15].
### Table 1. Stream data for Industrial Plant A with $\Delta T_{\text{min,pp}} = 20^\circ C$ (modified from Liew et al. [11])

| Stream | $T_i(\circ C)$ | $T_i(\circ C)$ | $\Delta H (MW)$ | $mCP (MW/\circ C)$ | $T_i(\circ C)$ | $T_i(\circ C)$ | Time (h) |
|--------|----------------|----------------|-----------------|-------------------|----------------|----------------|----------|
| A1 Hot | 170            | 80             | 5               | 0.06              | 160            | 70             | 00-24    |
| A2 Hot | 150            | 55             | 6.48            | 0.07              | 140            | 45             | 00-24    |
| A3 Cold| 25             | 100            | 15              | 0.2               | 35             | 110            | 00-24    |
| A4 Cold| 70             | 100            | 1.05            | 0.04              | 80             | 110            | 00-24    |
| A5 Cold| 30             | 65             | 5.25            | 0.15              | 40             | 75             | 00-24    |

### Table 2. Stream data for Industrial Plant B with $\Delta T_{\text{min,pp}} = 10^\circ C$ (modified from Liew et al. [11])

| Stream | $T_i(\circ C)$ | $T_i(\circ C)$ | $\Delta H (MW)$ | $mCP (MW/\circ C)$ | $T_i(\circ C)$ | $T_i(\circ C)$ | Time (h) |
|--------|----------------|----------------|-----------------|-------------------|----------------|----------------|----------|
| B1 Hot | 200            | 20             | 0.0005          | 0.08              | 195            | 15             | 06-20    |
| B2 Cold| 10             | 100            | 4               | 0.04              | 15             | 105            | 06-20    |
| B3 Cold| 100            | 120            | 10              | 0.5               | 105            | 125            | 20-06    |
| B4 Hot | 150            | 40             | 8.443           | 0.08              | 145            | 35             | 06-20    |
| B5 Cold| 60             | 110            | 1               | 0.02              | 65             | 115            | 06-17    |
| B6 Cold| 75             | 150            | 7               | 0.09              | 80             | 155            | 06-20    |

### Table 3. Stream data for Industrial Plant C with $\Delta T_{\text{min,pp}} = 20^\circ C$ (modified from Liew et al. [11])

| Stream | $T_i(\circ C)$ | $T_i(\circ C)$ | $\Delta H (MW)$ | $mCP (MW/\circ C)$ | $T_i(\circ C)$ | $T_i(\circ C)$ | Time (h) |
|--------|----------------|----------------|-----------------|-------------------|----------------|----------------|----------|
| C1 Hot | 85             | 40             | 225             | 5                 | 75             | 30             | 06-17    |
| C2 Hot | 80             | 40             | 400             | 10                | 70             | 30             | 06-17    |
| C3 Hot | 41             | 38             | 105.3           | 35.1              | 31             | 28             | 20-06    |
| C4 Cold| 25             | 65             | 23.6            | 0.5               | 35             | 75             | 20-06    |
| C5 Cold| 55             | 65             | 25.8            | 2.58              | 65             | 75             | 00-24    |
| C6 Cold| 33             | 60             | 6.48            | 0.24              | 43             | 70             | 06-17    |
| C7 Cold| 25             | 60             | 77              | 2.2               | 35             | 70             | 20-06    |
| C8 Cold| 30             | 240            | 29.4            | 0.14              | 40             | 250            | 06-17    |
| C9 Cold| 25             | 28             | 150             | 0.85              | 40             | 110            | 00-24    |
| C10 Cold| 30           | 100            | 59.5            | 0.85              | 40             | 110            | 00-24    |
| C11 Cold| 18            | 50             | 224             | 7                 | 28             | 60             | 06-17    |
| C12 Cold| 21           | 200            | 8.95            | 0.05              | 31             | 210            | 00-24    |

### Table 4. Stream data for Industrial Plant D with $\Delta T_{\text{min,pp}} = 10^\circ C$ (modified from Liew et al. [11])

| Stream | $T_i(\circ C)$ | $T_i(\circ C)$ | $\Delta H (MW)$ | $mCP (MW/\circ C)$ | $T_i(\circ C)$ | $T_i(\circ C)$ | Time (h) |
|--------|----------------|----------------|-----------------|-------------------|----------------|----------------|----------|
| D1 Cold| 15             | 60             | 149.85          | 3.33              | 20             | 65             | 00-24    |
| D2 Cold| 15             | 80             | 515             | 7.92              | 20             | 85             | 06-20    |

### Table 5. Multiple site utility temperatures

| Utility                  | Temperature (°C) |
|--------------------------|------------------|
| High-pressure steam (HPS)| 250              |
| Low-pressure steam (LPS) | 150              |
| Hot water (HW)           | 50               |
| Cooling water (CW)       | 20               |
| Chilled water (ChW)      | 10               |
The time slices are defined as temporal variation in demand streams. The identification of time slices in the demand site is necessary to determine the energy requirements when batch processes are incorporated. The time slices of streams are defined in three parts which are from 20 to 06 h, from 06 to 17 h and from 17 to 20 h. The third step in the method of TriGenSCA is the development of PTA to achieve Temperature Pinch Point as well as minimum heating and cooling required. The PTA is established in every part of time slice in each plant. The details of the procedure of developing the PTA can be seen in Linnhoff and Flower’s work [16]. Then, the work from Liew et al. [17] which developed MU PTA to obtain target potential sources and sinks of multiple utility levels is integrated with the TriGenSCA. The details MU PTA procedure can be referred to Liew et al.’s work [17]. The assumption has been made where the minimum temperature difference between process and utility for Plants A and C is 10°C whereas for Plants B and D is 5°C. Table 6 shows the summary of PTA and MU PTA in every time slice of each industrial plant. The TS PTA developed by Liew et al. [17] is then applied to satisfy the external utility requirement after the overall amount of utilities that can be shared between processes. The summary of TS PTA in each time slice is shown from Table 7. The sixth step in the implementation of TriGenSCA has been shown by Jamaluddin et al. [9] to reduce the targeting of power, heat and cool energy as well as to maximize the performance of the trigeneration system. The construction of TriGenSCA can be referred in Jamaluddin et al. [9]’s work. The final results show that the centralized trigeneration system required the supply of 618.79 MW of power, 14.18 MW of HPS, 348.33 MW of LPS, 253.1 MW of HW, 32.34 MW of CW and 0.11 MW of ChW.

The TriGenSST is a new approach in this methodology to determine a sensitivity of the Total Site Cooling, Heating and Power to industrial plant shutdown due to maintenance or upsets as well as for designing mitigation strategies. The TriGenSST has an advantage to manipulate data for various cases due to its numerical nature. In this case study, the data from each plant that has been shut down is omitted due to its numerical nature. In this case study, the data from each plant that has been shut down is omitted. The TriGenSST can be referred to Liew et al.’s work [17].

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Table 6. Summary of PTA and MU PTA

| PTA | Plant A | Plant B | Plant C | Plant D |
|-----|---------|---------|---------|---------|
| Time slices | 0 to 24 h | 6 to 17 h | 17 to 20 h | 20 to 6 h | 6 to 17 h | 17 to 20 h | 20 to 6 h | 6 to 20 h | 20 to 6 h |
| QH (MW/h) | 9.4 | 0 | 0 | 0 | 10 | 61 | 94.25 | 194.85 | 664.65 | 149.85 |
| QC (MW/h) | 0 | 11.85 | 12.85 | 0 | 0 | 181.87 | 0 | 105.3 | 0 | 0 |
| Temperature Pinch Point (°C) | 35 | 195 | 195 | 105 | 75 | 31 | 31 | 20 | 20 |

| MU PTA | HPS (MW/h) | 0 | 0 | 0 | 0 | 17 | 3 | 3 | 0 | 0 |
|        | LPS (MW/h) | 4.5 | -3.1 | -3.1 | 10 | 44 | 81.8 | 140.55 | 327.15 | 49.95 |
|        | HW (MW/h) | 4.15 | -6.15 | -7.15 | 0 | -156.07 | 9.45 | 51.3 | 337.5 | 99.9 |
|        | CW (MW/h) | 0 | -2.4 | -2.4 | 0 | -25.8 | 0 | -105.3 | 0 | 0 |
|        | ChW (MW/h) | 0 | -0.2 | -0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
### Table 7. Summary of TS PTA for all industrial plants

| Utility | External utility requirement (MW) |
|---------|----------------------------------|
|         | 6 to 17 h | 17 to 20 h | 20 to 6 h |
| HPS     | 17        | 3          | 3         |
| LPS     | 375.65    | 410.35     | 205       |
| HW      | 341.65    | 343.95     | 155.35    |
| CW      | 28.2      | 2.4        | 105.3     |
| ChW     | 0.2       | 0.2        | 0         |

### Table 8a. TriGenSST from 6 to 17 h

| Utility | Trigen (MW) | Normal operation (MW) | Excess/deficit from trigen (MW) | Plant A shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) | Plant B shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) |
|---------|-------------|-----------------------|--------------------------------|-----------------------|-----------------------------------|--------------------------------|-----------------------|-----------------------------------|--------------------------------|
| Power   | 618.79      | 611.67                | 7.12                           | 487.29                | 124.38                            | 131.5                          | 444.17                | 167.5                             | 174.62                          |
| HPS     | 14.18       | 17                    | -2.82                          | 17                    | 0                                 | -2.82                          | 17                    | 0                                 | -2.82                          |
| LPS     | 348.33      | 372.55                | -24.22                         | 368.05                | 4.5                               | -19.72                         | 375.65                | -3.1                              | -27.32                         |
| HW      | 253.1       | 179.43                | 73.67                          | 175.28                | 4.15                              | 77.82                          | 185.58                | -6.15                             | 67.52                          |
| CW      | 32.34       | 28.2                  | 4.14                           | 28.2                  | 0                                 | 4.14                           | 25.8                  | 2.4                               | 6.54                           |
| ChW     | 0.11        | 0.2 Pinch             | -0.09                          | 0.2 Pinch             | 0                                 | -0.09                          | 0 Pinch               | 0.2                               | 0.11                           |

### Table 8b. TriGenSST from 6 to 17 h

| Utility | Trigen (MW) | Normal operation (MW) | Excess/deficit from trigen (MW) | Plant C shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) | Plant D shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) |
|---------|-------------|-----------------------|--------------------------------|-----------------------|-----------------------------------|--------------------------------|-----------------------|-----------------------------------|--------------------------------|
| Power   | 618.79      | 611.67                | 7.12                           | 486.67                | 125                               | 132.12                         | 416.88                | 194.79                            | 201.91                          |
| HPS     | 14.18       | 17                    | -2.82                          | 0                     | 17                                | 14.18                          | 17                    | 0                                 | -2.82                          |
| LPS     | 348.33      | 372.55                | -24.22                         | 328.55                | 44                                | 19.78                          | 45.4                  | 327.15                            | 302.93                         |
| HW      | 253.1       | 179.43                | 73.67                          | 335.5                 | -156.07                           | -82.4                          | 179.43                | 0                                 | 73.67                          |
| CW      | 32.34       | 28.2                  | 4.14                           | 2.4                   | 25.8                              | 29.94                          | 28.2                  | 0                                 | 4.14                           |
| ChW     | 0.11        | 0.2 Pinch             | -0.09                          | 0.2 Pinch             | 0                                 | -0.09                          | 0 Pinch               | 0.2                               | -0.09                          |
### Table 9a. TriGenSST from 17 to 20 h

| Utility | Trigen (MW) | Normal operation (MW) | Excess/deficit from trigen (MW) | Plant A shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) | Plant B shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) |
|---------|-------------|------------------------|---------------------------------|-----------------------|-------------------------------------|---------------------------------|-----------------------|-------------------------------------|---------------------------------|
| Power   | 618.79      | 611.67                 | 7.12                            | 487.29                | 124.38                              | 131.5                           | 444.17                | 167.5                              | 174.62                          |
| HPS     | 14.18       | 3                      | 11.18                           | 3                     | 0                                   | 11.18                           | 3                     | 0                                   | 11.18                           |
| LPS     | 348.33      | 410.35                 | -62.02                          | 405.85                | 4.5                                 | -57.52                          | 413.45                | -3.1                               | -65.12                          |
| HW      | 253.1       | 343.95                 | -90.85                          | 339.8                 | 4.15                                | -86.7                           | 351.1                 | 7.15                               | -98                             |
| CW      | 32.34       | 2.4                    | 29.94                           | 2.4                   | 0                                   | 29.94                           | 0                     | 2.4                                | 32.34                           |
| ChW     | 0.11        | 0.2                    | Pinch                           | -0.09                 | 0                                   | -0.09                           | 0                     | 0.2                                | 0.11                            |

### Table 9b. TriGenSST from 17 to 20 h

| Utility | Trigen (MW) | Normal operation (MW) | Excess/deficit from trigen (MW) | Plant C shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) | Plant D shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) |
|---------|-------------|------------------------|---------------------------------|-----------------------|-------------------------------------|---------------------------------|-----------------------|-------------------------------------|---------------------------------|
| Power   | 618.79      | 611.67                 | 7.12                            | 486.67                | 125                                 | 132.12                          | 416.88                | 194.79                              | 201.91                          |
| HPS     | 14.18       | 3                      | 11.18                           | 0                     | 3                                   | 14.18                           | 3                     | 0                                   | 11.18                           |
| LPS     | 348.33      | 410.35                 | -62.02                          | 328.55                | 81.8                                | 19.78                           | 83.2                  | 327.15                              | 265.13                          |
| HW      | 253.1       | 343.95                 | -90.85                          | 334.5                 | 9.45                                | -81.4                           | 6.45                  | 337.5                               | 246.65                          |
| CW      | 32.34       | 2.4                    | 29.94                           | 2.4                   | 0                                   | 29.94                           | 2.4                   | 0                                   | 29.94                           |
| ChW     | 0.11        | 0.2                    | Pinch                           | -0.09                 | 0                                   | -0.09                           | 0.2                   | Pinch                              | -0.09                           |

### Table 10a. TriGenSST from 20 to 24 h

| Utility | Trigen (MW) | Normal operation (MW) | Excess/deficit from trigen (MW) | Plant A shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) | Plant B shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) |
|---------|-------------|------------------------|---------------------------------|-----------------------|-------------------------------------|---------------------------------|-----------------------|-------------------------------------|---------------------------------|
| Power   | 618.79      | 611.67                 | 7.12                            | 487.29                | 124.38                              | 131.5                           | 444.17                | 167.5                              | 174.62                          |
| HPS     | 14.18       | 3                      | 11.18                           | 3                     | 0                                   | 11.18                           | 3                     | 0                                   | 11.18                           |
| LPS     | 348.33      | 205                    | 143.33                          | 200.5                 | 4.5                                 | 147.83                          | 195                  | 10                                  | 153.33                          |
| HW      | 253.1       | 155.35                 | 97.75                           | 151.2                 | 4.15                                | 101.9                           | 155.35                | 0                                   | 97.75                           |
| CW      | 32.34       | 105.3                  | -72.96                          | 105.3                 | 0                                   | -72.96                          | 105.3                 | 0                                   | -72.96                          |
| ChW     | 0.11        | 0.11                   | Pinch                           | 0                     | 0                                   | 0.11                            | 0                     | 0                                   | 0.11                            |
Table 10b. TriGenSST from 20 to 24 h

| Utility | Trigen (MW) | Normal operation (MW) | Excess/deficit from trigen (MW) | Plant C shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) | Plant D shutdown (MW) | Variance from normal operation (MW) | Excess/deficit from trigen (MW) |
|---------|-------------|-----------------------|---------------------------------|-----------------------|-----------------------------------|---------------------------------|-----------------------|-----------------------------------|---------------------------------|
| Power   | 618.79      | 611.67                | 7.12                            | 486.67                | 125                               | 132.12                          | 416.88                | 194.79                            | 201.91                          |
| HPS     | 14.18       | 3                     | 11.18                           | 141.33                | 14.18                             | 3                               | 155.05                | 49.95                             | 193.28                          |
| LPS     | 348.33      | 205                   | 143.33                          | 64.45                 | 104.05                            | Pinch                           | 55.45                 | 99.9                              | 197.65                          |
| HW      | 253.1       | 155.35                | 97.75                           | 104.05                | 51.3                              | 149.05                          | 99.9                  | 197.65                            |
| CW      | 32.34       | 105.3 Pinch           | -72.96                          | 105.3                 | 0                                 | 0                               | 0                     | -72.96                            |
| ChW     | 0.11        | 0                     | 0.11                            | 0                     | 0                                 | 0                               | 0                     | 0.11                             |

3. Conclusions
The TriGenSST approach is developed from an extension of TriGenSCA to assess the sensitivity value of each plant shut down. Based on the results, extra 3.1 MW of LPS and 7.15 MW of HW are needed from the back-up system if Plant B is shut down as well as extra of 82.4 MW of HW is needed by the back-up system if Plant C is shut down. If Plants A and D are shutting down, surplus heat is supplied in the system. The size of the boiler and condensate system, hence, need to be improved to overcome the deficit energy as the Plants B and C are shut down. The TriGenSST can offer a sensitivity analysis on the sizing of utilities in the trigeneration system by assuming each plant shut down. The production of this extended TriGenSCA methodology will offer advantages to plant designers, managers and engineers to evaluate the exact utility value and hence, optimize the trigeneration system design.

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