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# Spatial Total Site Heat Integration Considering Energy Losses

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Energy Efficiency has been a research-intensive topic for almost four decades, initially driven by the expense of fossil fuels and then by environmental concerns. As one of the largest energy consumers, the industrial sector, particularly the process industry, has become the focus of energy efficiency research. Process Integration utilising Pinch Analysis plays a crucial role in improving the profitability and sustainability of industrial operations. Total Site Heat Integration (TSHI) is one of the primary branches of Process Integration based on Pinch Analysis, an industrial energy-saving method across individual process boundaries. However, the issue of plant layout has not been well addressed in the current Total Site (TS) targeting approaches. In this research, the Spatial Utility Problem Table Algorithm (SUPTA) is applied to the TSHI targeting methodology to account for the logistics of the process plants as well as the pressure drop, and heat losses caused by the effect of plant layout to achieve more accurate results that more accurately represent the actual plant situation. This enhanced tool can aid the designer in designing a Total Site Utility System that considers a new system's operational and capital costs by factoring in energy losses. A case study is performed to compare the maximum insulation (without energy losses) and conventional insulation with boiler condition adjustment (with energy losses). The result shows that the simple payback period has not significant difference at about 3 - 4 y, however, the scenario with maximal insulation has generally 3 times higher annual energy saving. The location of the utility plant is also found to be very significant in the TS utility system design, the results show that the simple payback period differs by 20 % when the utility plant is assumed at the middle of the industrial zone.

## 1. Introduction

In contemporary and industrial culture, energy plays an important part and is utilised in every human endeavour to create prosperity and the growth of a country (Bouzguenda et al., 2019). Since the beginning of the industrial revolution, the amount of energy consumed globally has steadily and rapidly increased. Because of this, energy recovery is required to lower energy use. Pinch Analysis (PA) results from systematic attempts to enhance heat recovery in the industrial sector through process integration. It improved industrial energy efficiency and savings in the 1970s (Linnhoff and Flower, 1978). The Pinch Analysis has expanded into the Total Site (TS) concept to investigate the possibility of conserving energy through centralised utility systems (Dhole and Linnhoff, 1993). The methodology of TS targeting is a component of an extended overall procedure that must be carried out to synthesise the TS System. The TS targeting method makes it possible to repurpose waste heat from one set of processes as a heat source for another.

Chew et al. (2013) state that huge distances between heat sources and sinks are essential to TS integration. The occurrence of pressure drops, and energy loss is possible within the steam headers, despite effective insulation and steam traps in the piping system. Numerous works on energy systems have taken distance into account. Liew et al. (2014b) proposed extending the Total Site Heat Integration (TSHI) targeting methodology for incorporating the pressure drop and heat loss during the site locations, aided by the TS Utility Distribution (TSUD) diagram. Chew et al. (2015) improved the TSHI methodology to consider the pressure drop in the

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pipelines of the utility system due to the process plant locations. Bütün et al. (2018) consider heat loss and temperature drop for long-distance heat transfer by proposing a Mixed Integer Linear Programming (MILP) to obtain optimal heat integration scenarios for multiple-location problems. Faramazi et al. (2019) developed a new method for targeting of TSHI, considering the streams optimum pressure drops ($\Delta$Ps). Plant-location-related parameters were included in the mathematical model that Bütün et al. (2019) developed for the MILP. Additionally, Wahab et al. (2022) considered the logistic of the process plants. They proposed a new methodology called the Spatial Utility Problem Table Algorithm (SUPTA) to determine pipelines' reverse flow and the let-down station's exact location.

Various well-established methodologies have been developed and applied in practical case studies to address the issue of heat integration within the TS. However, the research on TS Heat Integration has focused primarily on finding the energy target without considering plant distances. The required pipelines connecting plants in the TSHI are far longer than those needed inside a single unit. More attention must be paid to distance considerations as they incur additional costs resulting from pressure drops and heat losses. This paper develops an extended SUPTA methodology to address the consequences of plant layout that considers pressure drops and heat losses and its economic potential for considering energy losses. The energy loss mitigation design is also examined in this research to compare maximal insulation (no energy losses) and boiler operating conditions manipulation (with energy losses).

## 2. Methodology

The proposed methodology for targeting the minimum utility requirement of a TS system with spatial energy loss considerations for grassroots design problems is defined as follows.

### 2.1 Step 1: Data extraction

The data collection entails collecting information on the hot and cold streams across all processes within the TSHI boundary. This includes data on Supply Temperature ($T_s$), Target Temperature ($T_t$) and Enthalpy ($\Delta H$). It is necessary to collect data on the temperature of the utility system. It is imperative to gather information regarding the locations of the processes, with a particular emphasis on determining the availability of the existing utility pipeline design.

### 2.2 Step 2: Problem Table Algorithm (PTA) for each process

The data collected for each process should be analysed to determine the Pinch point's location. Identifying the heat sink and heat source in a process is facilitated by a pinch point, which holds significant importance. The transfer of heat energy from a higher temperature to a lower temperature, known as cascading, adheres to the principles of the first law of thermodynamics. Following the cascading process, the quantity of heat above the pinch point represents the minimum amount of heat necessary to satisfy the heat requirement, commonly referred to as the heat sink. The heat energy needed below the pinch point refers to the quantity of heat energy that must be cooled off, commonly referred to as the heat source.

### 2.3 Step 3: Multiple Utility Problem Table Algorithm (MU-PTA) for each process

The MU-PTA is designed to expand the PTA framework, aiming to optimise utility allocation within a specified temperature range for utilities (Liew et al., 2018). Identifying the Pinch point derived from the PTA methodology holds significance in segregating the heat sink region positioned above the Pinch point and the heat source region positioned below the Pinch point. The quantity of multiple utilities demanded above the Pinch regions corresponds to the quantity of heat utility consumed. In contrast, the quantity of multiple utilities demanded below the Pinch region corresponds to the heat generated.

### 2.4 Step 4: Plant location or utility distribution sequence identification

The identification of the plant location sequence has been determined for a new project. To facilitate the design of the utility distribution network, it is imperative to ascertain the precise distance between the process and utility plants. The designer is tasked with developing a utility distribution network for the subsequent phase, assuming each plant should receive utility supply directly from the primary utility header. It is imperative to ascertain the order in which utility transfers occur within the current pipeline infrastructure.

### 2.5 Step 5: Spatial Utility Problem Table Algorithm (SUPTA) for each utility header

The SUPTA is a Pinch-based Cascade Analysis for simultaneous targeting and designing the utility distribution system (Wahab et al., 2022). SUPTA targets the energy requirement for energy recovery across multiple processes or plants by considering the flow direction of the utility headers. The energy cascade in SUPTA is done according to the industrial process location and can easily identify the exact location for the let-down station and reverse flow pipeline.

### 2.6 Step 6: Calculation of energy losses

When steam is transferred through pipelines from one site to another in real-world scenarios, the pressure in the pipelines decreases, and heat is lost during the process. The pressure drop of pipelines can be calculated using the Babcock Equation (Chew et al., 2015), as shown in Eq(1), where $\Delta P$ is the pressure losses (N/m$^2$), W is the mass flow rate (kg/h), L is the length of the pipe (m), d is the internal diameter of the pipe (mm), and $\rho$ is the density (kg/m$^3$).

$$\Delta P = 2489 \cdot ((d + 3.6)/d^6) \cdot (W^2 L/\rho) \tag{1}$$

The heat losses caused by interplant heat transfer depend on the pipe geometry and the fluid temperature. This calculation takes into account heat losses from above-ground pipes. The heat loss from above-ground pipes is calculated using a simplified formula (Bütün et al, 2019), Eqs(2-5). It is assumed that the temperature of the pipe is the same as the fluid flowing through the pipe. The thickness of the pipe wall, denoted by $t_p$ (m), and the thickness of the insulating material, denoted by $t_i$ (m), U represents the overall heat transfer coefficient (W/m$^2$.K), A represents the surface area of the insulated pipe (m$^2$), and $T_{amb}$ represents the temperature of the air in the surrounding environment (°C), $Q_{sup}$ is the heat losses for supply pipes (kW) and $Q_{ret}$ is the heat losses for return pipes (kW).

$$\frac{1}{U} = \frac{1}{h_{air}} + \frac{t_p}{\lambda_p} + \frac{t_i}{\lambda_i} \tag{2}$$

$$A = 2\pi D_i L_p \tag{3}$$

$$Q_{sup} = UA(T_s - T_{amb}) \tag{4}$$

$$Q_{ret} = UA(T_r - T_{amb}) \tag{5}$$

### 2.7 Step 7: Target the minimum utility requirement considering energy losses

The energy losses only affected the multiple utility targeting stage, and the plant location remained the same. Step 3 and 5 are repeated, and a new column is added in SUPTA for the heat losses calculated. The heat losses deduct the net heat available.

### 2.8 Step 8: Economic analysis

A simple payback period will be calculated to determine the investment risk. The simple payback period will be calculated by using Eq(6). The case study should have a short payback period, indicating a low-risk project.

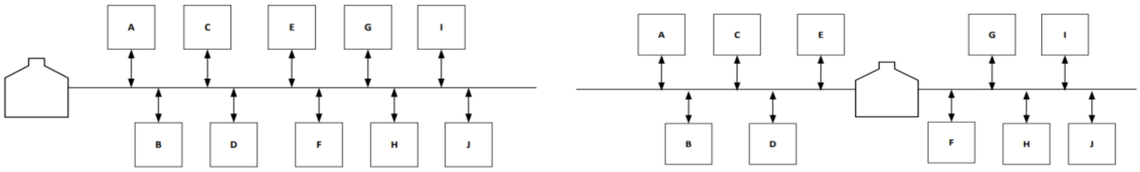
$$Simple\ payback\ period\ = \frac{Capital\ Cost}{Operating\ Cost\ Saving} \tag{6}$$

## 3. Case study

The methodology is demonstrated through utilizing a case study constructed using a petrochemical industry as its basis. This case study incorporates the modified stream and utility information presented in the work of Tarighaleslami et al. (2017). The case study includes a total of ten different processes, each of which is supported by a comprehensive range of five distinct types of steam utilities. The scenarios are distinguished by Scenario 1 without considering energy losses, which pumping stations and very thick insulation are assumed for mitigating the pressure drop and heat losses at the steam system. Scenario 2 for considering energy losses, which the pressure drops, and heat losses are assumed to be mitigated through increasing boiler pressure and load. In both scenarios, it is assumed that there is a distance of 1 km between the process plants and utility plants. The hypothetical arrangement or order of the plants is depicted in Figure 1, illustrating two scenarios: (A) utility plant at the end of the utility header and (B) utility plant at the middle of the utility header.

Table 1 shows the SUPTA for the High-Pressure Steam (Scenario 1A), where the utility plant is located at the end of the header, and the energy losses are not accounted for. Table 2 shows the SUPTA considering energy losses that added a new column for the heat losses (Scenario 2A). The step is the same as the previous SUPTA step, but the net heat available is deducted by the heat losses calculated. Table 3 summarizes the total heat sink and heat sources for each process in this case study, both with and without considering energy losses.

Based on Tables 4 and 5, it can be inferred that the utility located in the middle will exhibit more significant amounts of reverse flow compared to the utility situated at the end for both considering and without considering energy losses. Note that the number in the bracket represents the distance of the reverse flow. This is because fluid is capable of flowing only from locations of higher pressure to regions of lower pressure, necessitating a more significant amount of reverse flow. The reduction in reverse flow in scenarios considered for energy losses can be attributed to the decrease in excess heat resulting from energy losses.



Scenario (A)

Scenario (B)

*Figure 1: Examples of Utility distribution network, Scenario (A) utility plant at the end of the utility header and Scenario (B) utility plant located at the middle of the utility header*

*Table 1: The SUPTA without considering heat losses for High-Pressure Steam (Scenario 1A)*

| Plant | Heat Source ($\text{kW}_{\text{th}}$) | Heat Sink ($\text{kW}_{\text{th}}$) | Let-Down ($\text{kW}_{\text{th}}$) | Net Heat Requirement $NHR_i$ ($\text{kW}_{\text{th}}$) | Initial Heat Cascade $(Cascade_i)$ ($\text{kW}_{\text{th}}$) | Final Heat Cascade $(Cascade_i)$ ($\text{kW}_{\text{th}}$) | Balance Cascade $(Cascade_i)$ ($\text{kW}_{\text{th}}$) | Utility Demand $(Utility_i)$ ($\text{kW}_{\text{th}}$) | Reverse Flow Transfer ($\text{kW}_{\text{th}}$) | Final Utility Demand ($\text{kW}_{\text{th}}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Boiler | | | | | 0 | 9,278 | 0 | | | 8,934 |
| A | 0 | -3,532 | | -3,532 | -3,532 | 5,746 | 0 | 3,532 | | |
| B | 118 | 0 | | 118 | -3,414 | 5,864 | 118 | 0 | 86 | |
| C | 0 | -3,073 | | -3,073 | -6,487 | 2,791 | 118 | 3,073 | | |
| D | 0 | 0 | | 0 | -6,487 | 2,791 | 118 | 0 | | |
| E | 0 | -2,533 | | -2,533 | -9,020 | 258 | 118 | 2,533 | | |
| F | 0 | 0 | | 0 | -9,020 | 258 | 118 | 0 | | |
| G | 0 | 258 | | -258 | -9,278 | 0 | 0 | 258 | | |
| H | 0 | 0 | | 133 | -9,146 | 133 | -89 | -133 | 46 | |
| I | 133 | 0 | | 301 | -8,844 | 434 | -89 | -301 | 212 | |
| J | 301 | -89 | | -89 | -8,934 | 345 | 0 | 0 | | |

*Table 2: SUPTA considering heat losses for High-Pressure Steam (Scenario 2A)*

| Plant | Heat Source ($\text{kW}_{\text{th}}$) | Heat Sink ($\text{kW}_{\text{th}}$) | Let-Down ($\text{kW}_{\text{th}}$) | Heat Losses ($\text{kW}_{\text{th}}$) | Net Heat Requirement $NHR_i$ ($\text{kW}_{\text{th}}$) | Initial Heat Cascade $(Cascade_i)$ ($\text{kW}_{\text{th}}$) | Final Heat Cascade $(Cascade_i)$ ($\text{kW}_{\text{th}}$) | Balance Cascade $(Cascade_i)$ ($\text{kW}_{\text{th}}$) | Utility Demand $(Utility_i)$ ($\text{kW}_{\text{th}}$) | Reverse Flow Transfer ($\text{kW}_{\text{th}}$) | Final Utility Demand ($\text{kW}_{\text{th}}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Boiler | | | | | | 0 | 7,733 | 0 | | | 16,733 |
| A | 0 | -3,532 | | 54 | -3,478 | -3,478 | 4,255 | 0 | 3,478 | | |
| B | 118 | 0 | | 357 | 475 | -3,003 | 4,280 | 475 | | | |
| C | 0 | -3,073 | | 162 | -2,911 | -5,914 | 1,819 | 475 | 2,911 | | |
| D | 0 | 0 | | 0 | 0 | -5,914 | 1,819 | 475 | | | |
| E | 0 | -2,533 | | 297 | -2,263 | -8,177 | -444 | 475 | 2,263 | | |
| F | 0 | 0 | | 324 | 324 | -7,853 | -120 | 799 | | | |
| G | 0 | -258 | | 378 | 120 | -7,733 | 0 | 0 | | | |
| H | 133 | 0 | | 515 | 648 | -7,086 | 648 | 451 | | | |
| I | 301 | 0 | | 652 | 953 | -6,132 | 1,601 | 451 | | | |
| J | 0 | -89 | | 540 | 451 | -5,682 | 2,052 | 0 | | | |

All the results proceeded with their economic analysis to present their economic values without considering energy losses (Scenario 1) and with energy losses (Scenario 2). Scenario 1A (utility plant at the end) and 1B (utility plant in middle), which considered the TSHI in simplified conditions. These scenarios assume a thick pipe insulation layer was installed to mitigate heat losses, which the thickness is calculated based on the piping length and internal diameter, resulting the heat losses negligible. Scenario 2A (utility plant at the end) and 2B (utility plant in the middle) present more reliable and realistic scenarios, in which the heat losses from the piping on the targeted utility demand remains significant. The losses are mitigated via adjusting the temperature and pressure of the boiler, on top of the conventional insulation and steam trap installation.

*Table 3: Summary of utilities without considering energy losses and considering energy losses*

| | Scenario 1A & 1B | | Scenario 2A | | Scenario 2B | |
|---|---|---|---|---|---|---|
| Utility | Net Demand | Net Excess | Net Demand | Net Excess | Net Demand | Net Excess |
| HOL | 0 | 0 | 0 | 0 | 0 | 0 |
| VHPS | 11,976 | 0 | 3,898 | 0 | 815 | 0 |
| HPS | 8,934 | 0 | 13,805 | 0 | 15,951 | 0 |
| MPS | 211 | 0 | 4,286 | 0 | 4,957 | 0 |
| LPS | 0 | 4,226 | 0 | 3,440 | 0 | 2708 |

*Table 4: Result summary of Scenario 1A and 1B without considering energy losses*

| | Scenario 1A | | | | | Scenario 1B | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | HOL ($\text{kW}_{\text{th}}$) | VHPS ($\text{kW}_{\text{th}}$) | HPS ($\text{kW}_{\text{th}}$) | MPS ($\text{kW}_{\text{th}}$) | LPS ($\text{kW}_{\text{th}}$) | HOL ($\text{kW}_{\text{th}}$) | VHPS ($\text{kW}_{\text{th}}$) | HPS ($\text{kW}_{\text{th}}$) | MPS ($\text{kW}_{\text{th}}$) | LPS ($\text{kW}_{\text{th}}$) |
| **Final Target** | | | | | | | | | | |
| Net Load | 0 | 11,976 | 8,934 | 211 | 0 | 0 | 11,976 | 8,934 | 211 | 0 |
| Net Excess | 0 | 0 | 0 | 0 | 4,228 | 0 | 0 | 0 | 0 | 4,228 |
| **Let Down** | -2,451 | 2,451 | 0 | 0 | 0 | -2451 | 2,451 | 0 | 0 | 0 |
| **Reverse Flow** | 1,396 | 0 | 345 | 2,507 | 0 | 8,872 | 3,999 | 345 | 2,507 | 1,182 |
| Reverse flow (kW) [Distance (km)] | 1,396[1] | - | 212[2]<br>46[1]<br>86[3] | 261[1]<br>214[5]<br>1,002[7]<br>1,040[8] | - | 7,999[3]<br>873[8] | 1,910[3]<br>2,089[2] | 212[2]<br>46[1]<br>88[8] | 465[6]<br>399[8]<br>248[6]<br>355[4]<br>1,040[5] | 297[2]<br>885[3] |

*Table 5: Result summary of Scenario 2A and 2B considering energy losses*

| | Scenario 2A | | | | | Scenario 2B | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | HOL ($\text{kW}_{\text{th}}$) | VHPS ($\text{kW}_{\text{th}}$) | HPS ($\text{kW}_{\text{th}}$) | MPS ($\text{kW}_{\text{th}}$) | LPS ($\text{kW}_{\text{th}}$) | HOL ($\text{kW}_{\text{th}}$) | VHPS ($\text{kW}_{\text{th}}$) | HPS ($\text{kW}_{\text{th}}$) | MPS ($\text{kW}_{\text{th}}$) | LPS ($\text{kW}_{\text{th}}$) |
| **Final Target** | | | | | | | | | | |
| Net Load | 0 | 6,307 | 16,733 | 7,310 | 0 | 0 | 2,808 | 18,431 | 8,121 | 0 |
| Net Excess | 0 | 0 | 0 | 0 | 3,067 | 0 | 0 | 0 | 0 | 2,085 |
| **Let Down** | -6,393 | 6,393 | 0 | 0 | 0 | -6,505 | 6,505 | 0 | 0 | 1,495 |
| **Reverse Flow** | 909 | 0 | 0 | 0 | 419 | 5,381 | 0 | 0 | 0 | 1,495 |
| Reverse flow (kW) [Distance (km)] | 909[1] | - | - | - | 419[1] | 5,381[1] | - | - | - | 185[4]<br>314[2]<br>996[2] |

*Table 6: Summary of payback analysis for all scenarios*

| | Capital Cost (USD) | Operating Cost Saving (USD/y) | Simple Payback Period (y) |
|---|---|---|---|
| Scenario 1A | 9,799,019 | 5,089,835 | 3.17 |
| Scenario 1B | 13,423,732 | 5,089,835 | 4.35 |
| Scenario 2A | 3,505,416 | 1,863,807 | 3.10 |
| Scenario 2B | 3,914,703 | 1,851,288 | 3.48 |

The energy loss mitigation has a huge difference between Scenario 1 and 2. Thus economic impact is essential to be studied. A simple payback period is used to compare the economic potential in all scenarios in Table 6. The capital cost for piping is extracted from Wu and Wang (2017) and utility cost are extracted from Faramarzi et al. (2022). In general, Scenario 1 requires higher capital cost than Scenario 2, which the insulation cost is much higher. The operating cost savings are much higher for Scenario 2. However, the simple payback period shows similar potential for both scenarios except Scenario 1B, which is more than 4 y. Regarding the location of the utility plant, the scenarios featuring the utility plant in the middle (Scenario B) exhibit a higher payback period compared to the scenarios with the utility plant at the end (Scenario A), due to the inclusion of extra costs associated with piping and insulation for the reverse flow transfer. Therefore, the location of the utility plant is crucial for a grassroots design project.

## 4. Conclusions

This study presents an improved heat cascade algorithm to optimize energy recovery in various processes or facilities in real-world situations. The positioning of the utility plant plays a critical role in efficiently delivering heat, making it a crucial factor to consider during the design phase. The heat required for reverse flow for scenario with the utility plant at the end was three times greater than the scenario utility plant in the middle. The reduction in reverse flow in case studies considered for energy losses can be attributed to the decrease in excess heat resulting from energy losses. This research enables the designer to consider the energy losses mitigation design in a new TS Utility System through a rough operating and capital costs estimation. The scenario of maximal insulation (no energy losses) is more than 3 times higher in capital cost than the scenario that manipulates the boiler condition (with energy losses). The simple payback period is similar for all scenario ranges from 3 - 3.5 y, expect for Scenario 1B (maximal insulation, with utility plant at middle) at 4.4 y. However, the long-term operational cost savings for Scenario 1 with maximal insulation is more significant (about 3 times higher) than Scenario 2, which could make it much more interesting to certain industry. The methodology could be extended to encompass the vertical distance between the plant and the utility system. In certain instances, an increase in vertical distance may impact the overall distance between a plant and utility system. The methodology could also be considered for scatted tabulation of partnering process plants in the TS utility system.

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### References

Bouzguenda I., Alalouch C., Fava N., 2019, Towards smart sustainable cities: A review of the role digital citizen participation could play in advancing social sustainability, Sustainable Cities and Society, 50, 101627.

Bütün H., Kantor I., Maréchal F., 2018, A heat integration method with location dependent heat distribution losses, Computer Aided Chemical Engineering, 44, 1195-1200.

Bütün H., Kantor I., Maréchal F., 2019, Incorporating Location Aspects in Process Integration Methodology, Energies, 12 (17), 3338.

Chew K.H., Klemeš J.J., Wan Alwi S.R., Manan Z.A., Reverberi A.P., 2015, Total Site Heat Integration Considering Pressure Drops, Energies, 8(2), 1114-1137.

Chew K.H., Klemeš J.J., Wan Alwi S.R., Abdul Manan Z., 2013, Industrial implementation issues of Total Site Heat Integration, Applied Thermal Engineering, 61, 17–25.

Dhole V.R., Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions, and cooling, Computers & Chemical Engineering, 17, S101-S109.

Faramarzi S., Tahouni N., Panjeshahi M.H., 2019, Total Site Heat Integration Considering Optimum Pressure Drops, Chemical Engineering Transactions, 76, 1225-1230.

Faramarzi, S., Tahouni, N., Panjeshahi, M. H., 2022, Pressure drop optimization in total site targeting - a more realistic approach to energy- capital trade-off, Energy, 251, 123791.

Liew P.Y., Wan Alwi S.R., Ho W.S., Abdul Manan Z., Varbanov P.S., Klemeš J.J., 2018, Multi-period energy targeting for Total Site and Locally Integrated Energy Sectors with cascade Pinch Analysis, Energy, 155, 370-380.

Liew P.Y., Wan Alwi S.R., Klemeš J.J., 2014b, Total Site Heat Integration Targeting Algorithm Incorporating Plant Layout Issues, Computer Aided Chemical Engineering, 33, 1801-1806.

Linnhoff B., Flower J.R., 1978, Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks, AIChE Journal, 24(4), 633-642.

Tarighaleslami A.H., Walmsley T.G., Atkins M.J., Walmsley M.R.W., Liew P.Y., Neale J.R., 2017, A Unified Total Site Heat Integration targeting method for isothermal and non-isothermal utilities, Energy, 119, 10- 25.

Wahab A.S.A., Liew P.Y., Rozali N.E.M., Wan Alwi S.R., Klemeš J.J., 2022, Spatial Total Site Heat Integration Targeting using Cascade Pinch Analysis, Chemical Engineering Transactions, 94, 643-648.

Wu Y., Wang Y., 2017, A chemical industry area-wide layout design methodology for piping implementation, Chemical Engineering Research and Design, 118, 81–93.