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Spatial Total Site Heat Integration Targeting using Cascade Pinch Analysis

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Increasing population growth and rapid industrial development have become the main factors for increasing energy consumption. The increase in energy consumption increases the greenhouse gases released into the environment. The development of high energy efficiency equipment and energy optimisation tools and methodologies have been introduced to tackle the problem of harvesting renewable energy. Total Site Heat Integration (TSHI) is one of the energy optimisation methodologies applied in the industrial sector for site-wide function, which has proven to reduce energy consumption by analysing the result. The TSHI keeps being used by researchers to improve heat energy optimisation across individual processes until it covers the Locally Integrated Energy Sectors (LIES) concept. In this research, the TSHI targeting methodology is extended to consider the logistic of the process plants, known as the Spatial Utility Problem Table Algorithm (SUPTA). Steam headers are flowing in one direction. The plant location affects the entry point of steam generation and exit points of the steam consuming process. Steam generated from the downstream of the headers would need an additional reverse flow pipeline for sending it to the other plant located upstream of the pipeline. The energy cascade is done based on the spatial location, from the utility plant to the farthest process plant in the system. This spatial TSHI targeting methodology could be used for simultaneous targeting and design of site utility distribution system, which is beneficial for considering heat loss and pressure drop. A case study shows that the conventional TSHI and the novel SUPTA methodologies produce the same energy targetting result. However, it is shown that reverse flow pipelines increase threefold when the location of the utility plant change.

1. Introduction

United Nations' Sustainable Development Goals (SDGs) have been proposed as a mutual target between countries for ensuring sustainability on the mother earth. SDG 7 is targeted for doubling the improvement rate on energy efficiency for energy savings. Process Integration for the industrial process has been progressing for resources conservation, such as thermal energy, power, water, chemicals, hydrogen and carbon dioxide. Pinch analysis is a well-established methodology for process integration (Klemeš et al., 2018). Total Site Heat Integration (TSHI) is an extended Pinch Analysis methodology proposed for energy recovery across multiple process plants through a centralised utility system (Liew et al., 2017).

The method can be used to study energy conservation efficiently on an industrial symbiosis or eco-industrial park problem. Energy recovery opportunities could be found in a more extensive system boundary. Butturi et al. (2019) reviewed energy recovery potentials for industrial symbiosis in eco-industrial parks and urban-industrial symbiosis. Boldyryev et al. (2021) presented a design framework for Total Site energy recovery, which optimised the heat transfer area and capital cost for the heat exchanger network. Kröhling et al. (2022)

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recently proposed using a peer-to-peer automated negotiation mechanism to manage the peer exchange of utility to meet their generation and consumption in the eco-industrial parks.

The plant's location in the Total Site boundary is essential (Chew et al., 2013). The pressure drop and energy loss could happen with the steam headers, although the piping system is well insulated and has steam traps. Liew et al. (2014b) proposed an extension of the TSHI targeting methodology for incorporating the pressure drop and heat loss during the site locations, aided by the Total Site Utility Distribution (TSUD) diagram. Liew et al. (2014a) used a similar methodology to propose a new methodology for the grassroots design of heat and utility exchanger networks in the TSHI context. Chew et al. (2015) improved the TSHI methodology to consider the pressure drop in the pipelines of the utility system due to the process plant locations (horizontal utility transfer) and the plant equipment layout design (vertical utility transfer). Bütün et al. (2019) incorporated the factors relating to the plant location in the MILP mathematical model, such as distribution heat loss, above ground and underground heat loss, the pump works, and piping cost.

The conventional TSHI methodology could not directly target the energy requirement based on the distribution of the utility to various processes across the Total Site boundary. This research proposes a new Pinch-based cascade analysis, namely Spatial Utility Problem Table Algorithm (SUPTA), for representing the steady-state utility flow in the utility headers. The SUPTA target the energy requirement for each type of utilities individually. The cascade analysis is done for distributing the utility from the utility plant (hot oil heaters, boilers, cooling towers and chillers) to the farthest located process plant. The methodology considers for the reverse flow transfer that happens through rerouting of utility pipelines that is required to satisfy the utility requirement located at upstream process. The methodology also considers the possibility to let-down or heat transfer from higher to lower temperature utilities. The reverse flow transfer and let-down possibility allow the engineers to consider practical limitation at the site. The maximal use of reverse flow transfer and let-down options are returning the targeting result to be the same as the conventional TSHI targeting results. This methodology could be used for simultaneous targeting and design of site utility distribution system, which could be used to consider heat loss and pressure drop on utility headers. In addition, this methodology could directly guide the design of the utility network based on TSHI.

2. Methodology1

2.1 STEP 1: Data Collection

The data collection for hot and cold streams information for all the processes within the TSHI boundary, with supply temperature, target temperature, heat duty and heat capacity flowrate. The common utility system information (temperature) is required to be collected. The locations of the processes must be collected, in which the existing utility pipeline design should be known if available.

2.2 STEP 2: Multiple Utility Problem Table Algorithm (MU-PTA) for each Site/ Process

The MU-PTA is done in this step to target the utility requirement in a specific process, with maximal energy recovery potential assumed (Liew et al., 2018). Therefore, this step assumed that maximal energy recovery is achieved within the individual process before considering energy recovery through the utility system in TSHI.

2.3 STEP 3: Plant Location or Utility Distribution Sequence Identification

The plant location sequence is identified for a new project. The distance between the process and utility plants needs to be known for the design of the utility distribution network. The designer should design a utility distribution network for the next step, assuming the utility supply to each plant should be directly from the main utility header. The sequence of utility transfer from utility plants should be identified for the existing pipeline.

2.4 STEP 4: Spatial Utility Problem Table Algorithm (SUPTA) for each Utility Header

The development of SUPTA is required for each utility header, as shown in Tables 1 and 2, following the following steps:

i. Arrange the process plants from nearest to farthest from the utility plant (Column 1). Record the utility requirement as the heat source (positive value - Column 2) or the heat sink (negative value - Column 3). Record the energy obtained from let-down from higher temperature utility (Column 4). Calculate Net heat requirement (Colum 5) by summing the heat source, heat sink and supply from a let-down station.
ii. Construct the initial and final cascades ($Cascade_i$) using Eq. (1) in Column 6 and 7. The initial cascade initiates from 0, while the final cascade starts from the absolute value of the most negative value in the initial cascade. The Pinch (i_{pinch}) is located when 0 duty is found in the final cascade

$$Cascade_i = Cascade_{i-1} + NHR_i \quad (1)$$

Table 1: Spatial Utility Problem Table Algorithm (SUPTA) for Hot Oil header (Scenario (a))

1	2	3	4	5	6	7	8	9	10	11
Plant	Heat Source	Heat Sink	Let-down[a]	Net Heat Requirement (NHR_i)	Initial Heat Cascade $(Cascade_i)$	Final Heat Cascade $(Cascade_i)$	Balanced Cascade $(BCascade_i)$	Utility Demand $(Utility_i)$	Reverse flow transfer[b]	Final Utility Demand
Boiler					0	1,395.8	0			
A		-1,395.8		-1,395.8	-1395.8	0.0 **(Pinch)**	0.0 **(Pinch)**	1,395.8	-1,395.8	0
B	12,718.5			12,718.5	11,322.7	12,718.5	-8,871.5	-3847.0	1,395.8	-2,451.3
C				0	11,322.7	12,718.5	-8,871.5	0		
D				0	11,322.7	12,718.5	-8,871.5	0		
E		-7,998.6		-7,998.6	3,324.1	4,719.9	-872.9	0		
F				0	3,324.1	4,719.9	-872.9	0		
G				0	3,324.1	4,719.9	-872.9	0		
H				0	3,324.1	4,719.9	-872.9	0		
I		-872.9		-872.9	2,451.3	3,847.0	0.00	0		
J				0	2,451.3	3,847.0	0.00	0		

[a] received from higher temperature header;

[b] special piping for reverse direction flow and cross Pinch transfer, giver (positive value) and receiver (negative value)

Table 2: Spatial Utility Problem Table Algorithm (SUPTA) for Hot Oil header (Scenario (b))

Plant	Heat Source	Heat Sink	Let-down	Net Heat Requirement (NHR_i)	Initial Heat Cascade $(Cascade_i)$	Final Heat Cascade $(Cascade_i)$	Balanced Cascade $(BCascade_i)$	Utility Demand $(Utility_i)$	Reverse flow transfer	Final Utility Demand
Utility					0	7,998.6	0			
E		-7,998.6		-7,998.6	-7,998.6	0 **(Pinch)**	0 **(Pinch)**	7,998.6	-7,998.6	0
D				0	-7,998.6	0	0	0		
C				0	-7,998.6	0	0	0		
B	1,2718.5			12,718.51	4,719.9	12,718.5	-1,395.8	-11,322.7	8,871.5	-2,451.3
A		-1,395.8		-1,395.8	3,324.1	11,322.7	0	0		
Utility					0	872.9	0			
F				0	0	872.9	0	0		
G				0	0	872.9	0	0		
H				0	0	872.9	0	0		
I		-872.9		-872.9	-872.9	0 **(Pinch)**	0 **(Pinch)**	872.9	-872.9	0
J				0	-872.9	0	0	0		

iii. Construct the balanced cascades ($BCascade_i$) using Eq. (2) in Column 8, in which two similar equations are used for the above and below Pinch regions. For the above Pinch region, $Utility_i$ (Column 9) is added when there is a negative value in the $BCascade_i$ to make it zero. For the below Pinch region, negative $Utility_i$ is added when there is a positive value in the $BCascade_i$ to make it zero.

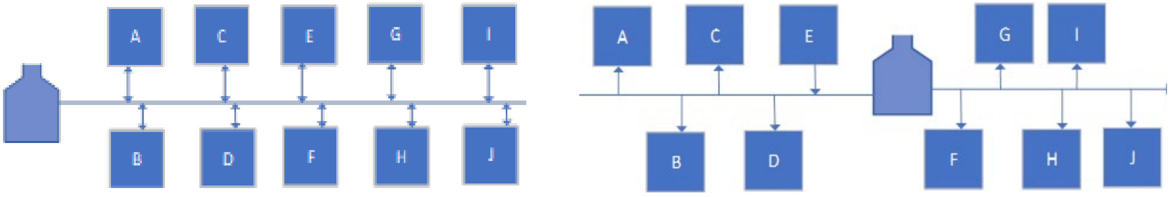
$$BCascade_i = \begin{cases} BCascade_{i-1} + NHR_i + Utility_i & from\ i = 0\ for\ i \leq i_{pinch} \\ BCascade_{i+1} + NHR_{i+1} + Utility_{i+1} & from \max i\ for\ i \geq i_{pinch} \end{cases} \tag{2}$$

iv. The utility demand could be reallocated by reverse flow transfer, which refers to rerouting the utility for transferring the utility in a reverse direction. This allows the steam generated from the later process in the header to be supplied to the earlier one. Record the transfer in Column 10 with a negative value for the supplying process and a positive value for the receiving process.

v. Calculate the final net utility demand in Column 11 by summing Columns 9 and 10. The positive values in this column represent demand from the boiler system, while the negative values indicate excess energy. The excess energy could be transferred to a lower temperature header through a let-down station.

3. Case Study

The methodology is demonstrated by an illustrative case study developed based on a petrochemical industry, with the modified stream and utility information in Tarighaleslami et al. (2017). There are ten processes in the case study, and five types of steam utilities serve it. The location or sequence of the plants is hypothetically assumed, as shown in Figure 1, with two situations, which are (a) utility plant at the end of the utility header and (b) utility plant located at the middle of the utility header. In both scenarios, the distance between the process plants and utility plants is assumed at 1 km away.



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

The heat sink and heat source for each process in this case study is done based on STEP 2 and summarised in Table 3, which is found using the MU-PTA methodology (Liew et al., 2018). In addition, the total heat source and sink available in the Total Site system are determined as mentioned in STEP 3, which the TSHI utility requirement targeting result is also summarised in Table 3.

Table 3: Summary of heat sinks and heat sources for each process

Process	Hot oil - HOL (kW)	Very High-Pressure Steam - VHPS (kW)	High-Pressure Steam - HPS (kW)	Medium-Pressure Steam - MPS (kW)	Low Pressure Steam - LPS (kW)
A	1,395.78	2,439.12	3,532.32	2,466.66	0
B	-12,718.51	-3,987.14	-117.99	-1,603.26	-1,693.5
C	0	0	3,072.8	248.4	0
D	0	2,088.9	0	0	296.96
E	7,998.63	6,848.12	2,532.8	1,606.16	885.15
F	0	0	0	-464.76	-1,454.52
G	0	4,109.5	258.18	0	0
H	0	2,060.054	-132.549	-1,001.729	-585.216
I	872.85	868.45	-301.3	-1,043.33	-1,818.34
J	0	0	89.28	3	141.47
Heat Source	12,719	3,987	552	4,113	5,552
Heat Sink	10,267	18,414	9,485	4,324	1,324
TSHI Target Requirement	0	11,976	8,934	211	-4,228

Table 1 shows the SUPTA (as mentioned in STEP 3) for the Hot Oil header under Scenario (a), in which the utility plant is located at the end of the header, which 1,395.8 kW of load on the Hot Oil heater, 3,847.0 kW of Hot Oil would require to be cool down. The targeted heater load and excess are further reduced to 2,451.3 kW of net energy excess by rerouting the piping from plant A to B to recover 1,395.8 kW of energy at the Hot Oil level. Meanwhile, Table 2 shows the SUPTA for the Hot Oil header under Scenario (b), in which the utility plant is located in between Plant E and F. The targeted Hot Oil heater load is 8,871.5 kW (7,998.6 kW for plant E and 872.9 kW for Plant I), while there is an excess of 11,322.7 kW at Plant B. The targeted heater load could be reduced by rerouting the Hot Oil from Plant B to Plant E and I, yielding an overall 2,451.3kW of net energy excess. It can be easily noticed that the final net energy excess is the same for both scenarios. Still, there is an additional piping cost and higher potential energy loss in Scenario 2.

The targeting result of Scenarios (a) and (b) (shown in Table 4) is the same as the conventional TSHI targeting results (Table 3). The let-down and reverse flow arrangements are summarised in Table 4. The amount of let-down is the same for Scenarios 1 and 2, also shown in the balanced cascade of the TS-PTA methodology. However, the reverse flow configuration differs from Scenarios 1 and 2 because the plant's location is the determining factor. In this case study, the amount of utility that needs reverse flow in Scenario 2 (16,905 kW) is threefold higher than in Scenario 1 (4,248 kW). The high amount of reverse flow indicates more capital cost is needed for the utility piping and insulation capital cost.

Table 4: Result summary for Scenario (a) and (b)

	Scenario (a)					Scenario (b)				
	HOL (kW)	VHPS (kW)	HPS (kW)	MPS (kW)	LPS (kW)	HOL (kW)	VHPS (kW)	HPS (kW)	MPS (kW)	LPS (kW)
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	-2,451	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] 46[1] 86[3]	261[1] 214[5] 1,002[7] 1,040[8]	-	7,999[3] 873[8]	1,910[3] 2,089[2]	212[2] 46[1] 88[8]	465[6] 399[8] 248[6] 355[4] 1,040[5]	297[2] 885[3]

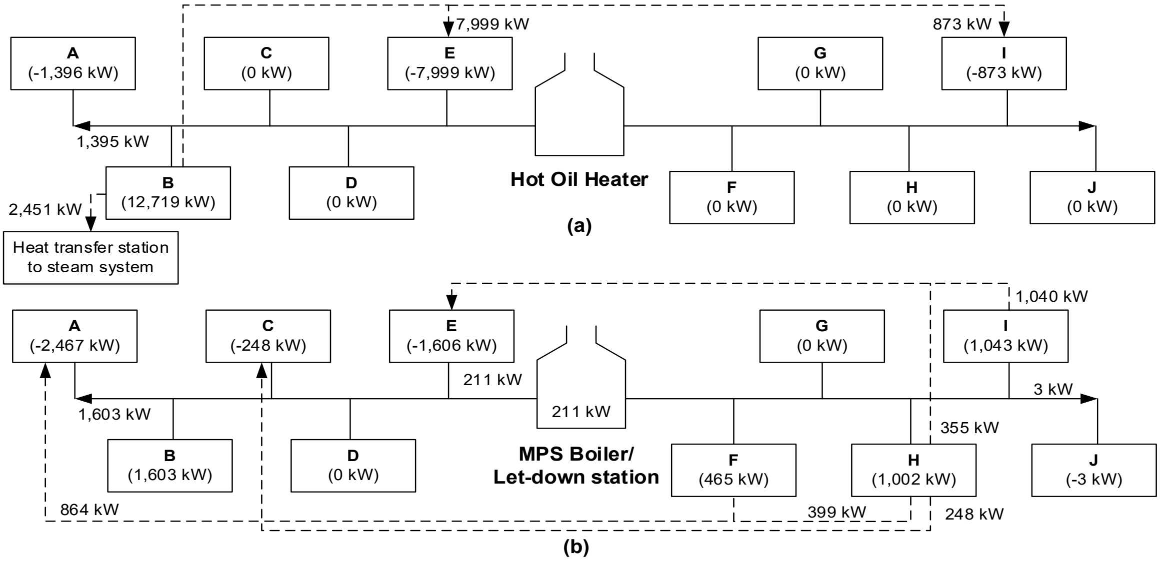


Figure 2: Design of distribution network in Scenario 2 for (a) Hot Oil and (b) MPS

For example, the Hot Oil and MPS distribution network through the utility headers in Scenario (b) for the Case Study is illustrated in Figure 2. The primary network (solid lines in Figure 2) cannot play a significant function as the primary energy sources come from the waste heat from other processes at the downstream in the system. The extra reverse flow piping system (dotted lines in Figure 2) increases the company's capital cost. In addition, it might represent a higher heat loss and pressure drop in the utility pipelines, which are subject to be optimised based on the situation. This result also indicates overall header flow direction could be reversed to minimise the reverse flow pipelines.

4. Conclusion

The flow direction of the utility headers is ignored in the Pinch-based TSHI methodology for targeting the energy requirement for energy recovery across multiple processes or plants. The Spatial Utility Problem Table Algorithm (SUPTA) is a Pinch-based Cascade Analysis proposed in this work for simultaneous targeting and designing the utility distribution system. The energy cascade in SUPTA is done according to the industrial process location. The exact location for the let-down station and reverse flow pipelines could be easily identified using SUPTA. The methodology could be extended for future research to incorporate the energy loss and pressure drops in the targeting results.

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References

Boldyryev S., Shamraev A.A., Shamraeva E.O., 2021, The design of the total site exchanger network with intermediate heat carriers: Theoretical insights and practical application, Energy, 223, 120023.

Butturi M.A., Lolli F., Sellitto M.A., Balugani E., Gamberini R., Rimini B., 2019, Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis, Applied Energy, 255, 113825.

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

Chew K.H., Klemeš J.J., Alwi S.R.W., 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(1), 17-25.

Klemeš J.J., Varbanov P.S., Walmsley T.G., Jia X., 2018, New directions in the implementation of Pinch Methodology (PM), Renewable and Sustainable Energy Reviews, 98, 439-468.

Kröhling D.E., Mione F., Hernández F., Martínez E.C., 2022, A peer-to-peer market for utility exchanges in Eco-Industrial Parks using automated negotiations, Expert Systems with Applications, 191, 116211.

Liew P.Y., Alwi S.R.W., Klemeš J.J., Varbanov P.S., Manan Z.A., 2014a, Utility-Heat Exchanger Grid Diagram: A tool for designing the total site heat exchanger network, Chemical Engineering Transactions, 39.

Liew P.Y., Theo W.L., Wan Alwi S.R., Lim J.S., Abdul Manan Z., Klemeš J.J., Varbanov P.S., 2017, Total Site Heat Integration planning and design for industrial, urban and renewable systems, Renewable and Sustainable Energy Reviews, 68, 964-985.

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.

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.