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The Optimization of Natural Gas Utilization Network in Single Region Using Pinch Analysis Method

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Natural gas is one of the cleanest energy resources and may have the potency to replace crude oil as the primary energy resource in several decades. A natural gas supply network should be developed to maximize the utilization of natural gas. Pinch analysis could be used to create the optimum natural gas network in single region supply-chain due to their different time scale, flowrate, and capacity. Therefore, in this study, a systematical method was developed to design a natural gas network system in a single region (East Java) using pinch analysis with 0-year and 3-year minimum time differences. The minimum time difference (Δt_{min}) represents the time delay of operation time in natural gas distribution. The concept of natural gas cascade calculation was introduced. The heuristics of natural gas pairing between source and sink streams in grid diagram analysis was developed. Using a 0-year minimum time difference gives the amount of unutilized supply with a value of 258.4 billion standard cubic feet (BSCF). In contrast, a 3-year minimum time difference gives the amount of alternative and unutilized supply with values of 639.3 BSCF and 897.7 BSCF, respectively. The grid diagram heuristics developed in this study provides the same results with the cascade calculation result. By knowing the amount of alternative supply and unutilized supply in a specific minimum time difference, it can be known the amount of required imported natural gas and the amount of exported natural gas based on the region and operating time span studied.

Keywords: Cascade table, Grid diagram heuristics, Natural gas network, Pinch analysis.

INTRODUCTION

Natural gas is one of the cleanest energy resources and may have the potency to replace crude oil as the primary energy resource in several decades (Nandari et al. 2016). Natural gas is also being the primary raw material in polymer and petrochemical industries (Liang et al. 2012). In Indonesia, there are 142.72

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trillion standard cubic feet (TSCF) of natural gas reserves. Based on current gas production at 2.9 TSCF/year, natural gas in Indonesia is expected to run out for the next 49 years (Ministry of Energy and Mineral Resource of Indonesia 2018). East Java province is one of the regions that has considerable natural gas reserves, and almost all of them are ready to be exploited. The availability of natural gas consumers in the East Java region is quite scattered and diverse, including the presence of petrochemical industry, gas power plants, gas-fueled transportation, and the gas requirement for domestic needs (Ministry of Energy and Mineral Resource of Indonesia 2018). Therefore, this region is very suitable to be used as a study and development in designing of the natural gas network in a single area.

Some aspects must be a concern in the development of the natural gas network, including the availability of natural gas resources, the availability of natural gas consumers, the operating time, and the capacity. Several alternative routes in the natural gas network and utilization are currently applied, such as pipeline gas, liquified natural gas (LNG), and compressed natural gas (CNG) (Karimi & Khan 2018). However, it is difficult to determine the most suitable network system to connect the supply and demand for natural gas due to their different time scale, flowrate, and capacity. Some studies are investigating the network system to connect the supply and demand for natural gas. Tan and Barton (2015) were reporting research about natural gas utilization from small-scale shale gas to become LNG and GTL with a multi-period approach. Tan and Barton (2016) renew their study by modifying the evaluation parameters using a stochastic program to resolve the uncertainty in the decision-making process. Al-Sobhi et al. (2018) developed a simulation and optimization framework for designing the natural gas network. Al-Sobhi et al. (2018) were reporting a study about natural gas utilization in the industrial cluster by considering the optimum gas supply locations and maximum profit, including LNG, GTL, and methanol. Wang et al. (2018) developed natural gas pipeline network based on the divide-and-conquer approach. Farzaneh-Gord and Rahbari (2018) have reported a study about the investigation of natural gas distribution network response in the variation of ambient temperature. Copiello (2018) was developed the economic assessment of the Italian natural gas network expansion to Sardinia Island.

The pinch analysis method has been used in the optimization of supply-demand in various applications in the scope of process system engineering,. Singhvi & Shenoy (2002) presented the graphical method to solve supply chain problems by considering time availability and material capacity. Foo et al. (2006) developed a surplus diagram and cascade analysis technique in a material network. Pinch analysis method can be used for the planning of carbon capture and storage (Ooi et al. 2012). The pinch design method can be utilized for multi-region carbon capture and storage network in Indonesia (Putra et al. 2018).

Based on our review in the open literature, there are no systematical methods in the determination of the optimum natural gas network in single region supply-chain using pinch analysis. The pinch design of the natural gas network in a single region is essential to give information most simply about the supply-demand network, maximum time delay allowed (minimum time difference), and the amount of alternative supply and unutilized supply. Therefore, in this study, a systematical method was developed to design the natural gas network system in a single region (East Java) using pinch analysis with different minimum time differences (Δt_{min}). There are two main steps in pinch analysis that considered in this study: cascade calculation and grid diagram development. The concept of natural gas cascade calculation was introduced. The heuristics of natural gas pairing between source and sink streams in grid diagram analysis was developed. The impact of Δt_{min} in the amount of recovered natural gas, unutilized supply, alternative supply, and grid diagram was also studied.

Table 1. Sources of natural gas in East Java (Ministry of Energy and Mineral Resource, 2018)

Code	Source Place	Start Time (year)	Duration (year)	End Time (year)	Natural Gas Production Rate (BSCF/year)	Natural Gas Capacity (BSCF)
SRM1	Madura Field 1	2	16	18	142.4	2278.4
SRM2	Madura Field 2	5	18	23	87.6	1576.8
SRG1	Gresik Field	3	13	16	34.7	451.1
SRB1	Bojonegoro Field	6	23	29	56.6	1301.8
SRL1	Lengo Field	7	23	30	25.6	588.8
Total Source						**6196.9**

BSCF = billion standard cubic feet

Table 2. Sinks of natural gas in East Java (Ministry of Energy and Mineral Resource, 2018)

Code	Sink Place	Start Time (year)	Duration (year)	End Time (year)	Natural Gas Consumption Rate (BSCF/year)	Consumed Natural Gas (BSCF)
SKP1	PT. Petrokimia	2	28	30	54.8	1534.4
SKG1	Gas Power Plants	3	22	25	113.2	2490.4
SKE1	PT. Pertamina Tuban	10	20	30	45.6	912.0
SKI1	Industrial Complex	4	16	20	54.8	876.8
SKR1	Domestic Gas	8	22	30	0.7	15.4
SKT1	Transportation Gas	5	15	20	7.3	109.5
Total Sink						5938.5

BSCF = billion standard cubic feet

RESEARCH METHODOLOGY

Data Compilation

In this research, the natural gas network is developed in single region coverage located in East Java. East Java region has fifteen sources (supply) points and sixteen sinks (demand) points. The number of source points is simplified to 5 points while the number of sink points is simplified to 6 points. The source and sink streams data used in this study are represented in codenames (SRM1, SKP1, etc.) and listed in Table 1 & 2. In the "Code" column in Tables 1 & 2, the mean of the first two letters of the stream code, namely "SR" and "SK" is source and sink, respectively. The third letter of the source streams code, such as "M, G, B, L" are Madura, Gresik, Bojonegoro, and Lengo, representing the source location, respectively. The third letter of the sink streams code such as "P, G, E, I, R, T" are petrochemical, gas power plant, energy infrastructure plant, industries, residences, and transportation, representing the sink stream's utilization, respectively.

The time availability, capacity, and flow rate of each source and sink points must be known as the network design parameters. Source time availability is when the natural gas reserve begins production and is ready to distribute to consumers until its depleted. Sink time availability is the time of consumer while already receive the natural gas supplies until the contract expires.

Cascade Table Analysis

Linnhoff and Hindmarsh (Linnhoff & Hindmarsh, 1983) created the pinch design method for the basis framework of heat exchanger network design. In this research, this pinch method was used as the basis framework of a single region natural gas network to obtain minimum alternative and unutilized supply. Source and sink flow rates are used as mass exchanged stream. The pinch point is obtained and indicating the time when no transfer between source and sink. Cascade table analysis is required to calculate the minimum alternative supply, minimum unutilized supply, and pinch point, which used to generate the grid diagram.

Analog with the minimum temperature difference (ΔT_{min}) in the pinch design method of heat exchanger network, this study proposed the minimum time difference (Δt_{min}), which represents the time delay of operation time in natural gas distribution because of unreadiness of source streams to produce natural gas. Therefore, Δt_{min} gives an impact on the shifting of start time and end time of the source streams. In this study, 0 and 3-year minimum time differences were used. The existence of Δt_{min} causes changes in the amount of recovered natural gas, unutilized supply, and alternative supply.

Grid Diagram Analysis

The design of the natural gas network can be developed using a grid diagram analysis. The following steps can genete grid diagram:

1. Horizontal lines were drawn, which represent each source and sink stream. The line was drawn from the left (start year) to the right (end year) with an appropriate year position.
2. The vertical line was drawn, which

represent the pinch point line.

3. Source-sink stream connection is started from the pinch line.
4. Grid diagram is divided into two zones, below pinch (left side of the pinch line) and above pinch (right side of the pinch line). The heuristics for connecting the source and sink streams in each zone were listed in Table 3.
5. In the pairing process between source and sink streams, the most similar start-end time between source and sink were first paired.
6. The most similar natural gas flowrate between source and sink streams are preferred pairing.

Table 3. Heuristics for grid diagram

Above pinch ($t \geq t_{pinch}$)	**Below pinch** ($t \leq t_{pinch}$)
There are no alternative supplies (sink streams must be depleted)	There are no unutilized supplies (source streams must be depleted)
Focus on the sink streams	Focus on the source streams
Flowrate source ≥ flowrate sink	Flowrate sink ≥ flowrate source
The splitting process usually happens in the sink stream	The splitting process usually happens in the source stream

RESULTS AND DISCUSSION

The natural gas network in a single region (East Java) was developed using pinch analysis with 0-year and 3-year minimum time differences. There are two main steps in pinch analysis that considered in this study: cascade calculation and grid diagram development.

Cascade Calculation Result

Cascade table analysis is used to calculate the minimum alternative supply, minimum unutilized supply, and pinch point, which used to generate the grid diagram. The correct cascade table calculation is essential because this calculation is used as the basis of the grid diagram development.

Table 4 shows the basis framework of the pinch method in designing the natural gas network. The contents of the table are t (time availability), source diagram, sink diagram, Δt (time interval), NG (natural gas) flow rate, NG (natural gas) load, infeasible, and feasible cascade. The source and sink streams were placed in a convenient year position at the source and sink column diagram. The time interval between source and sink can be expressed as Δt column. NG flow rate column contains source rate minus sink rate. NG load column contains Δt times NG flow rate. Infeasible NG cascade is obtained by accumulating the NG load from the beginning year to the end year. Feasible NG cascade is obtained by sum up the infeasible cascade with the positive value of the minimum one. The pinch can be found when the feasible cascade gives a value of zero, and this indicates that no flow at that year interval.

Table 4 shows the cascade calculation result of a single region with a 0-year minimum time difference (no operation time delay). As shown in Table 4, the pinch point of the studied area is obtained in year 2. With a 0-year minimum time difference (no operation time delay), the amount of unutilized supply is 258.4 BSCF. Because the pinch point is found in the earliest year of the start time, there is no alternative supply obtained in this scheme. Therefore, only one "above-pinch" zone was generated. By knowing the amount of unutilized supply of 120 BSCF with a 0-year minimum time difference, it can be concluded that the East Java region has excess natural gas production, which should be exported based on the operating time span in the absence of time delay.

Table 5 shows the cascade calculation result of a single region with a 3-year minimum time difference (operation time delay). Due to the operation time delay of each source stream, the pinch point was shiifted to year 8.

Table 4. The cascade calculation result of a single region with a 0-year minimum time difference (no operation time delay)

t (year)	Source streams, $S_{i,t}$ (BSCF/y)					Sink streams, $D_{j,t}$ (BSCF/y)						Δt (year)	Flow Rate NG (BSCF/ year)	Load NG (BSCF)	NG cascade (BSCF)	
															Infeasible	Feasible
2	SRM1, 142.4					SKP1, 54.8									0	0
	↓		34.7			↓	113					1	87.6	87.6		**(PINCH)**
3	↓		SRG1			↓	SKG1								87.6	87.6
	↓		↓			↓	↓		54.8			1	9.1	9.1		
4	↓		↓			↓	↓		SKI1						96.7	96.7
	↓	87.6	↓			↓	↓		↓		7.3	1	-45.7	-45.7		
5	↓	SRM2	↓			↓	↓		↓		SKT1				51	51
	↓	↓	↓	56.6		↓	↓		↓		↓	1	34.6	34.6		
6	↓	↓	↓	SRB1		↓	↓		↓		↓				85.6	85.6
	↓	↓	↓	↓	25.6	↓	↓		↓		↓	1	91.2	91.2		
7	↓	↓	↓	↓	SRL1	↓	↓		↓		↓				176.8	176.8
	↓	↓	↓	↓	↓	↓	↓		↓	0.7	↓	1	116.8	116.8		
8	↓	↓	↓	↓	↓	↓	↓		↓	SKR1	↓				293.6	293.6
	↓	↓	↓	↓	↓	↓	↓	45.6	↓	↓	↓	2	116.1	232.2		
10	↓	↓	↓	↓	↓	↓	↓	SKE1	↓	↓	↓				525.8	525.8
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	6	70.5	423		
16	↓	↓		↓	↓	↓	↓	↓	↓	↓	↓				948.8	948.8
	↓	↓		↓	↓	↓	↓	↓	↓	↓	↓	2	35.8	71.6		
18		↓		↓	↓	↓	↓	↓	↓	↓	↓				1020.4	1020.4
		↓		↓	↓	↓	↓	↓	↓	↓	↓	2	-106.6	-213.2		
20		↓		↓	↓	↓	↓	↓		↓					807.2	807.2
		↓		↓	↓	↓	↓	↓		↓		3	-44.5	-133.5		
23				↓	↓	↓	↓	↓		↓					673.7	673.7
				↓	↓	↓	↓	↓		↓		2	-132.1	-264.2		
25				↓	↓	↓		↓		↓					409.5	409.5
				↓	↓	↓		↓		↓		4	-18.9	-75.6		
29					↓	↓		↓		↓					333.9	333.9
					↓	↓		↓		↓		1	-75.5	-75.5		
30															258.4	258.4

Table 5. The cascade calculation result of single region with 3-year minimum time difference (operation time delay)

t (year)	Source streams, $S_{i,t}$ (BSCF/y)	Sink streams, $D_{j,t}$ (BSCF/y)	Δt (year)	Flow Rate NG (BSCF/ year)	Load NG (BSCF)	NG cascade (BSCF)	
						Infeasible	Feasible
2		SKP1, 54.8				0	639.3
		↓ 113	1	-54.8	-54.8		
3		↓ SKG1				-54.8	584.5
		↓ ↓ 54.8	1	-168	-168		
4		↓ ↓ SKI1				-222.8	416.5
	142	↓ ↓ ↓ 7.3	1	-222.8	-222.8		
5	SRM1	↓ ↓ ↓ SKT1				-445.6	193.7
	↓ 34.7	↓ ↓ ↓ ↓	1	-87.7	-87.7		
6	↓ SRG1	↓ ↓ ↓ ↓				-533.3	106
	↓ 87.6 ↓	↓ ↓ ↓ 0.7 ↓	2	-53	-106		
8	↓ SRM2 ↓	↓ ↓ ↓ SKR1 ↓				-639.3	0
	↓ ↓ ↓ 56.6	↓ ↓ ↓ ↓ ↓	1	33.9	33.9		**(PINCH)**
9	↓ ↓ ↓ SRB1	↓ ↓ ↓ ↓ ↓				-605.4	33.9
	↓ ↓ ↓ ↓ 25.6	↓ ↓ 45.6 ↓ ↓ ↓	1	90.5	90.5		
10	↓ ↓ ↓ ↓ SRL1	↓ ↓ SKE1 ↓ ↓ ↓				-514.9	124.4
	↓ ↓ ↓ ↓ ↓	↓ ↓ ↓ ↓ ↓ ↓	9	70.5	634.5		
19	↓ ↓ ↓ ↓	↓ ↓ ↓ ↓ ↓ ↓				119.6	758.9
	↓ ↓ ↓ ↓	↓ ↓ ↓ ↓ ↓ ↓	1	35.8	35.8		
20	↓ ↓ ↓ ↓	↓ ↓ ↓ ↓				155.4	794.7
	↓ ↓ ↓ ↓	↓ ↓ ↓ ↓	1	97.9	97.9		
21	↓ ↓ ↓	↓ ↓ ↓ ↓				253.3	892.6
	↓ ↓ ↓	↓ ↓ ↓ ↓	4	-44.5	-178		
25	↓ ↓ ↓	↓ ↓ ↓				75.3	714.6
	↓ ↓ ↓	↓ ↓ ↓	1	68.7	68.7		
26	↓ ↓	↓ ↓ ↓				144	783.3
	↓ ↓	↓ ↓ ↓	4	-18.9	-75.6		
30	↓ ↓					68.4	707.7
	↓ ↓		2	82.2	164.4		
32	↓					232.8	872.1
	↓		1	25.6	25.6		
33						258.4	897.7

Table 5 shows that in the existing 3-year operation time delay, the amount of alternative supply is 639.3 BSCF, and the amount of unutilized supply is 897.7 BSCF. Because the pinch point is found in the middle of the source and sink streams, there are two zones separated by pinch line: below pinch and above pinch. For the studied region, the higher values of operation time delay, then the amount of alternative and unutilized supply is increasing. By knowing the amount of alternative and unutilized supply with a 3-year minimum time difference, it can be concluded that the East Java region requires imports of natural gas of 639.3 BSCF and should be exported natural gas of 897.7 BSCF which based on this study.

Grid Diagram Development

The prediction of the natural gas network based on cascade calculation can be described using grid diagram analysis. Figure 1 shows the grid diagram of the natural gas network in a single region with a 0-year minimum time difference. As shown in Figure 1, the connections between source and sink streams to exchange natural gas are developed according to the heuristics. There are some stream splitting in sink streams to match each stream 's flow rate of according to "above pinch" heuristics. The total amount of unutilized supply obtained from the grid diagram gives the same results with the cascade table calculation.

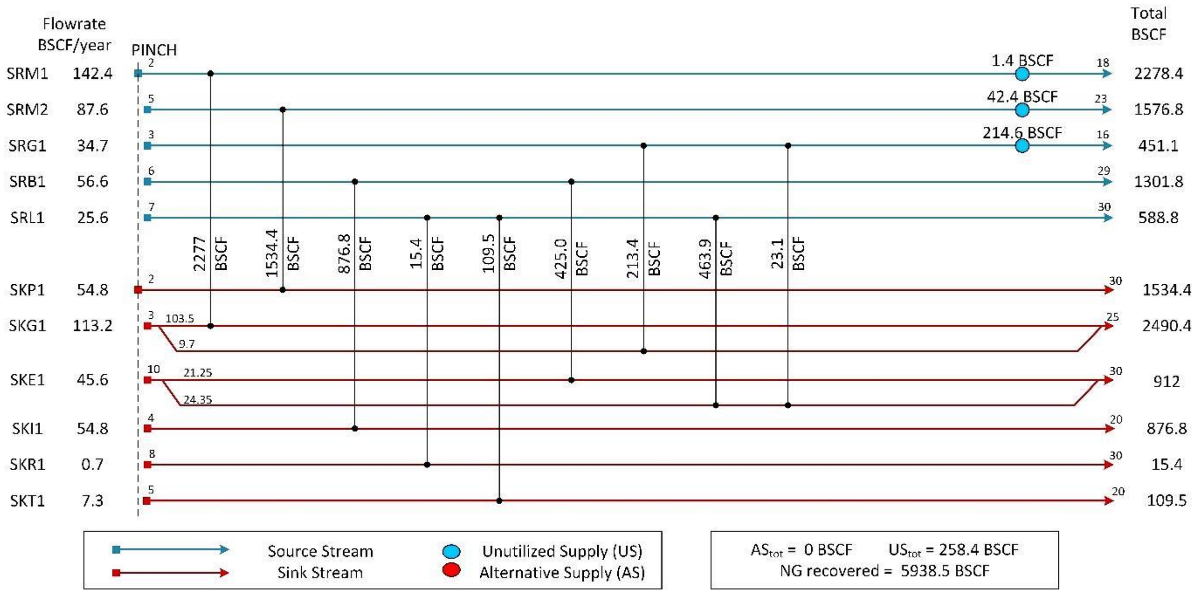

Fig. 1: The grid diagram of the natural gas network in a single region with a 0-year minimum time difference

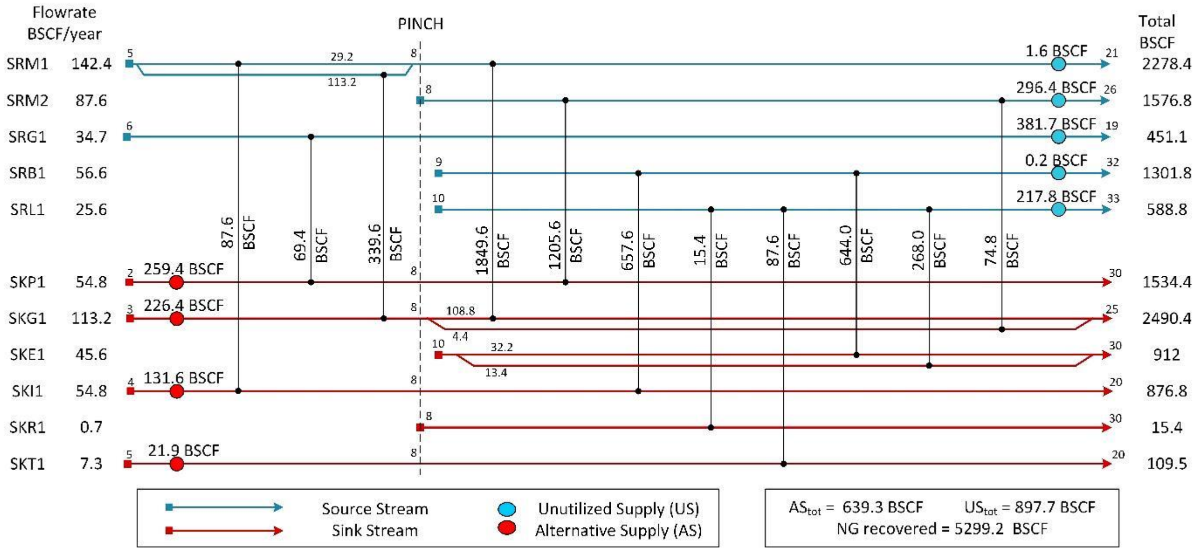

Fig. 2: The grid diagram of the natural gas network in a single region with a 3-year minimum time difference

Figure 2 shows the grid diagram of the natural gas network in a single region with a 3-year minimum time difference. As shown in Figure 2, the connections between source and sink streams to exchange natural gas are developed according to the heuristics. There are some stream splitting in source and sink streams to match the flow rate of each stream according to "below pinch" and "above pinch" heuristics. The total amount of unutilized supply and alternative supply obtained from the grid diagram gives the same results with the cascade table calculation.

The results from the cascade calculation and the grid diagram show that the natural gas network developed in this study has a similar analogy with heat exchanger network design by Linnhoff & Hindmarsh (1983). Compared to Ooi et al. (2012) and Putra et al. (2018), the natural gas network has different design philosophy with carbon capture and storage network because the value of the commodities used are quite different (natural gas is valued product while carbon dioxide is waste material).

CONCLUSION

The optimum natural gas network in a single region (East Java) was developed using pinch analysis with 0 and 3-year minimum time differences. The concept of natural gas cascade calculation has been introduced. The heuristics of natural gas pairing between source and sink streams in grid diagram analysis have been developed. Using a 0-year minimum time difference gives the amount of unutilized supply with a value of 258.4 BSCF. In comparison, a 3-year minimum time difference gives the amount of alternative and unutilized supply with a value of 639.3 BSCF and 897.7 BSCF. The grid diagram heuristics developed in this study provides the same results with the cascade calculation result. By knowing the amount of alternative supply and unutilized supply in a specific minimum time difference, it can be known the amount of required imported natural gas and the amount of exported natural gas based on the region and operating time span studied.

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