Maneuverability study and economic analysis for tugboat procurement in basin area

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Abstract. The growth of the energy industry in Indonesia is increasing rapidly. This study concern about the crude and product oil distribution of one of the biggest oil companies in Indonesia. The distribution of crude and product oil requires large capacity particularly designed bunker transportation, which is an oil tanker. However, the enormous size of the tanker causes the tanker must be assisted by a tugboat to berth at the port of any type of waters. In this study, the simulations were conducted at the Marine Region (MR) III of Tanjung Priok Port, which has a basin-shaped berthing area, to determine the needs of tugboats force based on the size of the tankers. The simulations were carried out in MATLAB software by considering Tankers’ principal dimension, environmental data, Tugboat force (Bollard Pull; BP), and Tugboat’s heading angle. Then, those forces should be combined with each other into several scenarios and reviewed its economics based on the “buy”, “lease”, and “combination” scenario, calculated in the Capital Expenditure and Operational Expenditure factors.

1. Introduction
The growth of the energy industry in Indonesia is growing rapidly, along with the increasing number of companies engaged in the energy sector and the growing number of companies that have been established for a long time. The company has a role to explore, produce, develop renewable gas and energy from upstream to downstream. Products from companies in the energy sector will be transported to consumers, hence it needs transportation with large capacity and specially designed bunker, which is Tankers.

The company’s Tankers has various size, including VLCC Vessel. Because of its enormous size, the ship must be assisted by a tugboat to berth at the port. Based on Regulation of Minister 57, the year of 2015 article 1 paragraph (2), written that “The uses of Tugboat are to push, pull, or assist a vessel to/from any mooring facilities”. Besides that, based on Regulation of Minister 57, the year of 2015 article 38 paragraph (3), written the minimum of Power and Bollard Pull to tow a vessel, according to the Length of the vessel [1]. Those regulations must be followed to enhance the effectiveness and efficiency of any towing process.
Table 1. PM 57 / 2015 Article 38 Paragraph (3)

| Length of Vessel | Amount of Tugboat | Power       | Bollard Pull                  |
|------------------|-------------------|-------------|-------------------------------|
| 70 – 150 meter   | Minimum 1 unit    | Minimum 2000 HP | Minimum 24ton bollard pull   |
| 150 - 250 meter  | Minimum 2 units   | Minimum 6000 HP | Minimum 65ton bollard pull   |
| 250 meter or above | Minimum 3 units | Minimum 11000 HP | Minimum 125ton bollard pull   |

According to the passage above, it can be inferred that there is a need to decide the most technically, especially in maneuverability, and economically efficient tugboats, while it still fulfilling the safety factors and government regulations regarding piloting and towing at the company. In this study, a maneuverability simulation for tugboat procurement needs to be carried out. Ship maneuvering should be performed for predicting the navigation safety in restricted areas [2].

The simulations carried out in software by entering the principal dimension of the Tankers, environmental data, the Tugboat force, and the Tugboat’s heading angle. The output of those simulations is the minimum Bollard Pull to tow the Tankers, and in the end, it will provide optimal economy in the procurement of tugboats.

2. Methodology

2.1. Company general data

Marine Region (MR) III is located in Tanjung Priok, DKI Jakarta, Indonesia. As a big port in the capital city of Indonesia, MR. III Tanjung Priok is fully equipped with 4 Jetties that facilitate Tankers with a minimum of 1,200 DWT and a maximum of 30,000 DWT. Besides that, MR. III Tanjung Priok also has assets such as Lightweight Small Boat, Fire Fighting Equipment, and Oil Leakage Treatment Equipment.

In general, a tugboat has 2 propellers to help the maneuver process in a berthing area. The tugboat will be operated in a towing process. Conventional Propellers have a nozzle to increase the Bollard value and its effectiveness. The nozzle can be mounted on a fixed propeller equipped with a rudder or movable propeller (Kort nozzle) [3], [4].

Tugboats owned or rented by the company uses an Azimuth Thruster type propulsion system that has many advantages over using conventional propulsion as below.

1. Ability to produce optimal thrust in all directions
2. Does not require a rudder
3. Improve ship maneuverability
4. Improve electrical efficiency
5. Provide more space in the engine room
6. Reducing maintenance costs

MATLAB (Matrix Laboratory) is a software used to do numerical computing with computer programming languages and a matrix basis. The software can help to solve mathematical problems by making mathematical simulations and modeling. In this study, it was used to carry out simulations in the selection of alternative scenarios in order to produce recommendations for the most effective and efficient scenario of tugboats and their respective power.

In this process, each scenario will be simulated to get the result of the minimum Bollard Pull to tow the Tankers of each cluster. This simulation needs some data, such as:

1. Tanker Principal Dimension
2. Environmental Data
3. Tugboat Force (Bollard Pull)
4. Tugboat Heading Angle

2.2. Mathematical Maneuvering Group Model
Ship maneuvering can be simulated with the hydrodynamic derivatives using a mathematical model such as Maneuvering Modeling Group (MMG) [5]. Maneuvering Modeling Group (MMG) model is one of the most widely used method for ship maneuvering motion simulations because it is possible to take the hull-rudder-propeller interaction into account [5]–[7]. MMG model was firstly developed and proposed by a research group called Maneuvering Modeling Group (MMG) in Japanese Towing Tank Conference (JTTC) [7]. This study refers to the concept for maneuvering simulations presented in MMG model to predict the maneuvering of tugboats.

As shown in figure 1, the simulation model designed based on a few parameters, such as hull, rudder, and propeller as a form of response from environmental factors like wind and waves [8]–[10]. It will use formulas of 3 (three) degrees of freedom such as written below. It will be equipped with an estimation formula to calculate the value of hull forces and hull moments as in the formula below. The $\beta$ variable is interpreted as a drift angle and the $r$ variable is defined as the turning rate [8], [10].

![Mathematical Maneuvering Group Model](image)

Figure 1. Mathematical Maneuvering Group Model

\[
\begin{align*}
\text{Surge} & : (m + m_x)u_G - (m + m_y)v_G = X_H + X_P + X_R + X_W + X_T \\
\text{Sway} & : (m + m_y)v_G + (m + m_x)u_G = Y_H + Y_P + Y_R + Y_W + Y_T \\
\text{Yaw} & : (J_{zz} + J_{xx})r = (N_H + N_P + N_R + N_W + N_T) - x_G (Y_H + Y_P + Y_R + Y_W + Y_T) \\
X_H + m_y v_G & : 0.5 p L d U^2 \{X'_{0} + X'_{r \rho \beta} + (X'_{r} - m_{y} \beta r') + (X'_{r r} - x'_{r} m_{y} \beta r')^2 + X'_{r r r \rho \beta} \} \\
Y_H - m_x u_G & : 0.5 p L d U^2 \{Y'_{\rho \beta} + (Y'_{r} - m_{x} \beta r') + Y'_{r r} \beta r' + Y'_{r r r} \beta r' + Y'_{r r r r} \beta r' \} \\
N_H & : 0.5 p L d U^2 \{N'_{\rho \beta} + N'_{r r} + N'_{r r r \rho \beta} + N'_{r r r \rho \beta}^2\beta r' + N'_{r r r r} \beta r' \}
\end{align*}
\]

Hull derivatives coefficient used to simulate the towing process are equipped with the parameter below [2].

\[
\begin{align*}
Y'_{\beta} & : Y'_{\beta 0} (1 + 0.54r^2) \\
Y'_{r} - m'_{x} & : (Y'_{r} - m'_{x})_0 (1 + 1.82r^2) \\
N'_{\beta} & : N'_{\beta 0} (1 - 0.85r^2) \\
N'_{r} & : N'_{r 0} (1 + 0.33r^2) \\
Y'_{\rho 0} & : 0.5 \pi k + 1.4C_b / (L/B) \\
(Y'_{r} - m'_{x})_0 & : 0.5C_b / (L/B)
\end{align*}
\]
\[ N'_{\beta 0} : k \]
\[ N'_{\rho 0} : 0.54k + k^2 \]
\[ k : 2d/L \]
\[ X'_{\beta \beta} : 1.15C_b / (L/B) - 0.18 \]
\[ X'_{\beta r} - m'_{y} : -1.91C_b / (L/B) + 0.08 \]
\[ X'_{\rho r} + x'_{g} m'_{y} : -0.085C_b / (L/B) + 0.008 \]
\[ X'_{\beta \rho \rho} : -6.68C_b / (L/B) + 1.10 \]
\[ Y'_{\beta \rho \rho} : 0.185L/B + 0.48 \]
\[ Y'_{\beta r} : 0.97\tau'/C_b - 0.75 \]
\[ Y'_{\rho r} : 0.26(1 - C_b) L/B + 0.11 \]
\[ Y'_{\rho r} : 0.069\tau' - 0.051 \]
\[ N'_{\beta \rho \rho} : 0.69C_b + 0.66 \]
\[ N'_{\beta r} : 1.55C_b / (L/B) - 0.76 \]
\[ N'_{\rho r} : 0.075(1 - C_b) L/B - 0.098 \]
\[ N'_{\rho r} : 0.25C_b / (L/B) - 0.056 \]

To complete the hull derivates coefficient formula as in the formula below, additional longitudinal mass (\(m_x\)), transverse additional mass (\(m_y\)), and the mass of additional moment of inertia (\(J_{zz}\)) values are needed, which can be calculated based on Motor Diagram. In this calculation, the values of \(m_x\), \(m_y\), \(J_{zz}\), and \(I_{zz}\) (moment of inertia) can also be calculated through the following equation [8].

\[ m_x : 0.0098 \left( \frac{L}{2} \right)^2 d \]
\[ m_y : 0.1370 \left( \frac{L}{2} \right)^2 d \]
\[ J_{zz} : 0.00634 \left( \frac{L}{2} \right)^4 d \]
\[ I_{zz} : \left( \frac{1}{8} \right) \left( \frac{L}{2} \right)^2 \left( \frac{L}{2} \right)^4 d = \left( \frac{1}{16} \right) mL^2 \]

Then, the lateral force and moment that exerted by the propeller can be calculated by some formula or by looking at the KT-Js diagram. In this study, the rudder force can be neglected as the effect of full tugboat assists operation.

2.3. Economic feasibility

The economic feasibility calculation will be divided into 2 (two) scenarios, such as the “Buying” Scenario and the “Rent” Scenario. Each scenario will be compared through its Capital Expenditure value and Operational Expenditure value for the next 20 years.

3. Results and discussion

3.1. Tankers clustering

To design the cluster of tankers, this study needs the TPPR (Tanker Port Performance Report) data of MR. III Tanjung Priok. According to the TPPR data, can be inferred that the frequency of tankers that berth to MR. III Tanjung Priok in the last 5 (five) years for each mooring facility did not have a significant difference. Each mooring facility has a berthing call on an average of 1 (one) to 3 (three) tankers so that in the cluster design process there is no need to forecast tankers for the next few years. In addition, tankers rely on MR. III Tanjung Priok mooring facilities are mostly vessels owned by companies and subsidiaries.
### Table 2. Tankers Cluster Based on 2018’s TPPR

| Cluster | DWT (ton)            | T     | LOA (m) | Types of Tanker          | Vessel | Arrival |
|---------|----------------------|-------|---------|--------------------------|--------|---------|
| A       | 1,329 - 6,842        | FLUCTUATIVE | 65 - 158 | Small 1 & 2 + SPOB       | 27     | 135     |
| B       | 7,079 - 23,479       | 96 - 160 | General P. |                              | 43     | 216     |
| C       | 25,161 - 47,236      | 133 - 184 | Medium R. & Large R. |                              | 32     | 141     |
| **TOTAL** | **102**           |       | **492** |                          |        |         |

3.2. Real scheme of towing in MR. III Tanjung Priok

Towing activities in MR. III Tanjung Priok is carried out by pulling, pushing, and sliding the tankers until it reaches the mooring facility. MR. III Tanjung Priok has a basin-shaped berthing area, thus tankers must turn off its engine and do a full tugboat assist. Tankers may lean on both its portside and starboard. When a tanker agreed to lean on it portside, it must be rotated in a basin turning area before entering the mooring area.

**Figure 2.** Real Towing Scheme on MR. III Tanjung Priok for Tankers with LOA ≤ 100m

In Figure 2, the scheme shown is the process of berthing a Tanker with LOA ≤ 100m using only one (1) Tugboat. Note that the images of tankers and tugboats shown on the figure are scaled and might not match the actual ship's size and position at sea. By looking at the figure, in area 1, the Tanker is available to still use its own speed with a maximum of 5 knots at a safe speed. In area 2, tugboats are deployed to help maneuver the ship around the turn. Approaching area 4 (basin 4), the ship needs to stop the engine and the tug will pull the tanker so that it will enter backward in area 5. Furthermore, the tug will direct the tanker to lean on areas 6 and 7. Since there’s only one (1) Tugboat that assists the ship, the tug needs to create an angle ease the process of leaning the ship to the jetty later on. For the final Tanker leaning process, its tug might pull the ship’s aft and rely on the ship’s movement influenced by the external factors [11]. Towing is required to keep the ship at a safe speed and not hardly bump the jetty.

While in Figure 3, the scheme shown is the process of berthing a tanker with LOA > 100 m using two (2) Tugboats. As in the previous figure, the images of tankers and tugboats shown on the figure are scaled and might not match the actual ship's size and position at sea. In area 1, the tanker can still use
its own speed with a maximum of 5 knots at a safe speed. In area 2, tugboats are deployed to help maneuver the ship around the turn. Approaching area 4 (basin 4), the ship will need to stop the engine and the tug will pull the tanker so that it will enter backward in area 5. Furthermore, the tug will push the tanker to the mooring facility in area 6.

![Real Towing Scheme on MR. III Tanjung Priok for Tankers with LOA > 100m](image)

**Figure 3.** Real Towing Scheme on MR. III Tanjung Priok for Tankers with LOA > 100m

### 3.3. Tankers data for simulation

To simulate the towing process in MR. III Tanjung Priok, this study needs Tankers to represent each cluster. Tankers shown in Table 3 are the biggest Tankers from each cluster. It can be assumed that if any Tugboat can tow these 3 (three) Tankers, thus those tugboats will surely tow smaller Tankers.

| Parameter | Cluster A       | Cluster B       | Cluster C       |
|-----------|-----------------|-----------------|-----------------|
| DWT       | 6842 ton        | 23479 ton       | 47236 ton       |
| LOA       | 100.5 m         | 159.98 m        | 182.5 m         |
| B         | 18 m            | 25.6 m          | 32.2 m          |
| H         | 9.5 m           | 16.4 m          | 19.1 m          |
| F         | 6.8 m           | 5.5 m           | 6.45 m          |

### 3.4. Environmental data

The MR. III Tanjung Priok has fairly normal environmental conditions with wind speeds ranging from 4 knots to 15 knots and wave heights of 0.3 – 0.8 meters. The depth of water in the outer basin is approximately 11 meters and in the inner basin is approximately 9 – 10 meters. In addition, tides that occur on the port are in the range of 0.6 to 1.1 meters. The current velocity taken at the mooring facilities areas when at high tide is 0.3 knots from the direction of 45 to 50° and at low tide is 1.1 knots from the direction of 230°.
Figure 4. Simulation Result of Cluster A on Area 2 using 1 Tugboat

Figure 5. Simulation Result of Cluster B on Area 2 using 1 Tugboat

Figure 6. Simulation Result of Cluster C on Area 2 using 1 Tugboat
Figure 7. Simulation Result of Cluster A on Area 4 using 1 Tugboat

Figure 8. Simulation Result of Cluster B on Area 2 using 1 Tugboat

Figure 9. Simulation Result of Cluster C on Area 2 using 1 Tugboat
3.5. Simulation result
The simulation of the towing process in MR. III Tanjung Priok is divided into 2 (two) main areas, such as the Basin Entering Area (Area 2) and Basin Turning Area (Area 4). The output taken from this simulation is the distance of towing represented by the X and Y-axis.

The simulation results as drawn by Figure 4 to Figure 6, are simulated on Area 2 using 1 Tugboat, towed by 135°. In figure 4, Cluster A towed with Tugboat of 22ton Bollard Pull. In figure 5, Cluster B towed with the Tugboat of 32ton Bollard Pull. In figure 6, Cluster C towed with Tugboat of 38ton Bollard Pull.

The simulation results as drawn by Figure 7 to Figure 9, are simulated on Area 4 using 1 Tugboat, towed by 290°. In figure 7, Cluster A towed with Tugboat of 22ton Bollard Pull. In figure 8, Cluster B towed with the Tugboat of 32ton Bollard Pull. In figure 9, Cluster C towed with Tugboat of 38ton Bollard Pull. The movement of the tanker and tugboat is from point 0 on the y0 axis, which Tankers is rotated like in Figure 2 and Figure 3.

From the figures above, it can be inferred that Tankers in each cluster must be towed with a different force, according to its size. The combination that may occur in Economic Feasibility from the simulation above is the buy/rent a combination of 22ton and 32ton, 22ton and 38ton, 32ton and 38ton, or 22ton, 32ton, and 38ton. The simulation can be continued to as much as Tugboat used as possible.

Table 4. Tabulation of Simulation Result

| Cluster | 1 TUG | 2 TUGs | 3 TUGs |
|---------|-------|--------|--------|
|         | 22ton | 20ton  | 15ton  |
| A       |       |        | 15ton  |
|         |       | 15ton  | 10ton  |
| B       | 32ton | 22ton  | 20ton  |
|         |       | 20ton  | 15ton  |
|         |       |        | 10ton  |
| C       | 38ton | 32ton  | 22ton  |
|         |       | 22ton  | 20ton  |
|         |       |        | 15ton  |

3.6. Tabulation of simulation result
According to the simulation done by using MATLAB software, this study can infer the minimum value of Bollard Pull to be used by each cluster and succeed to tow Tankers in every turning point. Besides that, the value of minimum Bollard Pulls also exerted by the amount of Tug. The value can be seen in Table 4 about the Tabulation of Simulation Result. Then, this tabulation would be a consideration to determine and inspect the technical analysis in the next step.

3.7. Technical analysis
The tabulation of the minimum Bollard Pull value in Table 4 needs to be evaluated by the parameter of the Tugboat dimension based on Table 5. The tugboat dimension is important to make sure that the Tugboats are on equal height with the Tankers towed. Tugboat with the Bollard Pull of 32ton and 38ton are higher than the Tankers cluster A so that those only can push Tankers cluster B and C.
Table 5. Dimensional Parameter of Tugboat

| Bollard Pull | LOA     | B      | T      | Cluster can be Pushed |
|--------------|---------|--------|--------|-----------------------|
| 10ton        | 15 - 30 m | 6 - 7 m | 2.5 m  | A, B, C               |
| 15ton        | 15 - 30 m | 6 - 7 m | 3 m    | A, B, C               |
| 20ton        | 20 - 30 m | 8 - 9 m | 3.5 m  | A, B, C               |
| 22ton        | 25 - 30 m | 8 - 9 m | 3.5 m  | A, B, C               |
| 32ton        | 26 - 35 m | 8 - 9 m | 4 m    | B, C                  |
| 38ton        | 27 - 36 m | 8 - 10 m| 4.5 m  | B, C                  |

Table 6. Summary of technical analysis

| TUG                  | Based on Operational (refer to Table 4)                                        | Based on Dimensional (refer to Table 5)                                      |
|----------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| 10ton                | Lower force than needed to tow Tankers Cluster C                                | -                                                                              |
| 15ton, 20ton, 22ton  | May towing the Tankers Cluster C with the addition of bigger forced tugboat    | -                                                                              |
| 32ton, 38ton         | -                                                                              | Higher than Tankers Cluster A                                                 |

The tabulation of technical analysis could also be seen in Table 6, where each Bollard Pull of Tugboat has its own capability to tow or push Tankers. Then, the result of the Technical Analysis would be a consideration to calculate the economic feasibility.

3.8. Economic Feasibility

In this study, the economic feasibility is calculated based on Capital Expenditure and Operational Expenditure in order to find the cheapest procurement combination of the Tugboat for MR. III Tanjung Priok. The economic feasibility will be divided into 3 (three) scenarios, such as “Buying” Scenario, “Rent” Scenario, and “Buy-Rent” Scenario. Furthermore, each scenario will be calculated for the next 20 years. Table 7 representing the buy scenario costs of each Tugboat, while Table 8 representing the rental costs of each Tugboat. The total costs of the “Buying” scenario are an accumulation of investment costs in its first year with some operational costs, escalated by 2% each year. Operational costs including the prices of BBM, daily operational, periodic survey, port management, insurance, and administration.

Table 7. Buying scenario costs for 20 years of each Tugboat

| HP Tug | BP Tug (ton) | Operational + Fuel (per month) x IDR 1,000,000 | Buying Price + Additional Cost x IDR 1,000,000 | Buying Price + ((Operational + Fuel) 20 Years) x IDR 1,000,000 |
|--------|--------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------------------------|
| 2 x 600 HP | 10 | 623 | 11,110 | 193,756 |
| 2 x 650 HP | 15 | 653 | 12,120 | 203,762 |
| 2 x 800 HP | 20 | 775 | 15,150 | 242,528 |
| 2 x 1200 HP | 22 | 858 | 23,230 | 275,803 |
| 2 x 1500 HP | 32 | 892 | 36,360 | 299,979 |
| 2 x 1600 HP | 38 | 964 | 38,380 | 323,333 |
Table 8. Rental Costs for 20 Years of Each Tugboat

| HP Tug | BP Tug (ton) | Rent/month (Without Fuel) x IDR 1,000,000 | Rent for 20 Years + Fuel x IDR 1,000,000 |
|--------|--------------|------------------------------------------|------------------------------------------|
| 2 x 600 HP | 10 | 666 | 220,358 |
| 2 x 650 HP | 15 | 704 | 231,478 |
| 2 x 800 HP | 20 | 818 | 264,835 |
| 2 x 1200 HP | 22 | 960 | 306,252 |
| 2 x 1500 HP | 32 | 1,002 | 318,418 |
| 2 x 1600 HP | 38 | 1,093 | 344,833 |

Table 9. Economic Feasibility Result

| TUG | Price of TUG1 x IDR 1000000 | Price of TUG2 x IDR 1000000 | Price of TUG3 x IDR 1000000 | Total Price 20 Year + BBM x IDR 1000000 |
|-----|-----------------------------|-----------------------------|-----------------------------|-----------------------------------------|
| Buy | 22ton-32ton | 275,803 | 299,979 | 575,782 |
| Buy-Rent | 22ton-32ton | [Buy] 275,803 | [Rent] 318,418 | [Buy-Rent] 594,221 |
| Buy | 22ton-38ton | 275,803 | 323,333 | 599,134 |
| Rent-Buy | 22ton-32ton | [Rent] 306,252 | [Buy] 299,979 | 606,231 |
| Buy-Rent | 22ton-38ton | [Buy] 275,803 | [Rent] 344,833 | 620,636 |
| Rent | 22ton-32ton | 306,252 | 318,418 | 624,670 |
| Rent-Buy | 22ton-38ton | [Rent] 306,252 | [Buy] 323,333 | 629,585 |
| Rent | 22ton-38ton | 306,252 | 344,833 | 651,086 |
| Buy | 15ton-22ton-20ton | 203,762 | 275,803 | 242,528 | 722,094 |
| Buy | 15ton-32ton-20ton | 203,762 | 299,979 | 242,528 | 746,269 |

The total costs of the “Rental” scenario are an accumulation of investment costs each year, escalated by 2% each year, with its fuel costs which also escalated by 2% each year. Investment costs including the fuel, daily operational, periodic survey, port management, insurance, and administration, and the margin for the renter company.

4. Conclusion

1. Towing activities in MR. III Tanjung Priok allows Tankers to lean on both its portside and starboard. When a tanker agreed to lean on it portside, it must be rotated in a basin turning area before entering the mooring area.
2. Based on the simulation, each cluster can be towed by 1 (one) to 3 (three) Tugboats with a different force (ton) and heading angle. For Tankers Cluster A, it can be towed by minimum Tugboats with 15ton-10ton-10ton Bollard Pull, while Tankers Cluster B can be towed by
minimum Tugboats with 20ton-15ton-10ton Bollard Pull. Then, Tankers Cluster C can be towed by minimum Tugboats with 22ton-20ton-15ton Bollard Pull.

3. The economic feasibility was calculated by both of its economical parameter and regulation parameters. Tugboats must still refer to the Government Regulation to maintain safety and security factors. The 3 (three) cheapest combination that the company can get should be the “Buy” Scenario of 22ton-32ton, “Buy-Rent” Scenario of “22ton-32ton” and “Buy” Scenario of “22ton-38ton”.

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