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Mitigating Port Congestion Amid Geopolitical Tension: A Focus On Key Causes and Strategic Solutions

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Abstract

Port congestion is a critical issue that poses significant operational, economic, and environmental challenges to port terminals across the world. This paper explores various consequences of port congestion through a comprehensive analysis of key performance indicators such as total port stay times, prolonged anchorage and operation durations. The study has utilized descriptive statistics and regression analysis with data collected from 1 September 2023 to 1 September 2024, we then assess how these factors correlate with congestion levels in various international port terminals. Descriptive statistics revealed high variability in vessel timings, with extreme outliers, while regression analysis confirmed that all three factors show significance in impacting port operations. Prolonged congestions disrupt supply chain operation durations, delay cargo deliveries, and even escalate operational costs for shipping companies which ultimately impacts the competitiveness of ports on a global scale. By identifying the critical factors contributing to port congestion and their implications, this research underscores the urgent need for strategic interventions. Future work will focus on vessel stay times at the Port of Singapore to uncover unique operational challenges and trends, while comparing vessel stay time patterns with broader trends identified in this study. Additionally, the outcomes of this study not only aim to assist Singapore in mitigating its port congestion issues, but also to strive to provide valuable insights for other major ports aspiring to enhance their global competitiveness and ensure reliable supply chain operations.

Keywords
Port congestion, Port terminal, Total port stay time, Anchorage time and Operation time

1. Introduction

Sea transportation is a foundation of the global economy which contributes over 80% of global trades (Humphreys, 2023). It is essential for the import and export of goods, connecting countries, being cost-effective and efficient, as well as facilitating international commerce (García, 2021). As maritime industry continues to flourish and adapt to changes, sea transportation's role in global commerce will remain significant.

Port terminals can be seen as an indispensable component for sea transportation and global trades, which directly impact on the country's economy growth, supply chain resilience, and logistics efficiency. It plays an important role in connecting various transportation modes such as ships, trucks, and trains to allow a seamless flow of goods and services from the beginning till it reaches the end consumer.

Major port terminals like Singapore, handles millions of containers annually due to its strategic location such as shipping routes that connects Asia with the Middle East, America, and Europe (Gordon et al., 2005). This allows ships to have shorter transit times to their destination points and reduced shipping cost, making Singapore an essential pit stop for global trades. However, port congestion trends remain a significant global challenge where they are characterised by issues such as increase in trade volumes, rise of e-commerce demand, increase in shipping cost, equipment shortages, labour shortages, poor weather conditions, and more (Beacon Newsroom, 2024). These factors cause significant bottleneck situations at port terminals such as Singapore's, affecting shipping schedules which leads to disrupted global supply chain. Port congestions can potentially decrease overall operational efficiency of the port terminal due to unforeseen delays and bottlenecks which causes reduced productivity (The Maritime Executive, 2024). Longer waiting times for cargo vessels to berth will lead to delays in loading and unloading operations. Shipping lines may incur higher cost due to longer vessel turnaround times and extra fuel consumption because of longer idle period while waiting for berths (Sreelakshmi H K, 2024).

1.1 Objectives

This research will focus on conducting empirical analysis of the key causes contributing to port congestion amid geopolitical tensions. The study aims to identify specific factors that exacerbate congestion issues. Following the identification of the various causes, the research study will explore strategic solutions to alleviate congestion which helps with enhancing overall supply chain reliability and efficiency of port terminal.

2. Literature Review

Through this literature review, we will be reviewing on causes of port congestions, performance indicators to measure port terminal effectiveness, and possible economic impacts in the long run.

2.1 Causes of port congestions impacting maritime supply chain

Wendler-Bosco & Nicholson (2019) highlights the impacts of port disruptions such as delays, increased costs, and extreme weather events could cause ripple effects in the global supply chain. When ships are delayed at port terminals, cargoes are loaded onto trucks and ships outside of their specific requested schedules, leading to longer overall transit times and mess up the arrival pattern of vessels (Guo et al., 2023). Also, ongoing geopolitical tension affects shipping in the Red Sea and Suez Canal region. With the Houthi attacks on vessels to be persisting, many vessels have chosen to take the longer route around the Cape of Good Hope (Notteboom et al., 2024). The avoidance of the Red Sea and Suez Canal region leads to a significant impact on the global shipping routes, costs, and delivery times which causes operational challenges such as reduced efficiency and capacity constraints due to schedule disruptions (Morgan, 2024). This shows that port congestion can be seen as a multifaceted issue that arises from a combination of infrastructure limitations, demand surges, operational inefficiencies, and external disruptions (Wendler-Bosco & Nicholson, 2019).

2.2 Performance indicators to measure port terminal effectiveness during port congestion

Wendler-Bosco & Nicholson (2019) mentioned about unreliability of vessel schedules due to port congestion. In search for a feasible solution, Qu et al. (2024) introduced a mixed-integer nonlinear programming model that incorporates a queuing theory model that is based on the prediction of the vessel's waiting time, a liner schedule design model, and a container handling efficiency selection mechanism. The study provides a comprehensive approach to liner schedule design and was implemented to a real-life scenario which proves to have the capability to handle most real-world scenarios (Qu et al., 2024). However, the study did not test on unforeseen situations such as extreme weather conditions or geopolitical conflicts which may question the model's effectiveness. Also, Zhang et al. (2023)

utilised the Automatic Identification System (AIS) data to test on three port status indicators which are total port TEU (Tportteu), total berth TEU (Tberthteu), and ship waiting ratio (waitratio) to investigate on how reliable the indicators are to predict port status. Through the study, it shows that it could provide significant accuracy to allow shipping companies and port operators to allow them to factor in possible port congestion. However, the study's sample size is small which have potential limitation in generalisability.

2.3 Long-term economic impacts

Wendler-Bosco & Nicholson (2019) mentioned about how port disruption leads to undesirable economic impact to a country. Also, Guo et al. (2023) mentioned about the negative impacts that port congestion can do to a country's economy. It shows how port congestion impacts on trade efficiency, causing a ripple effect on supply chains. The disruption of trade flows, disrupts the flow of goods, leading to delay in shipping schedules. This inefficiency results to increasing shipping cost, longer waiting time for vessels which means higher operational costs for shipping companies. It will then pass down to consumers through higher freight rates, leading to inflation and increasing the cost of imported goods. Also, with the disruption, it may cause a decline in export which may impact the country's gross domestic product (GDP) growth, slowing down economic growth. A study found that due to port congestion, US foreign trade was 24.5% lesser between May and November 2021, resulting a loss of $15.7 billion (Steinbach, 2022). Over time, these issues can slow economic grow due to losing attractiveness for foreign investments, losing global competitiveness and influence in global trade.

3. Methods

To address the research objective of finding potential solutions to ease port congestions issues at port terminals and enhance supply chain reliability, this study employes statistical model such as descriptive and regression analysis to analyse historical data on port traffic. Specifically, the study focuses on vessel arrival and departure times, total port stay time, anchorage time, operation time and time of berthing. These indicators will be useful to identify peak congestions period and congestions patterns happening at port terminals. Also, we will be utilising real-time data from port management systems to monitor the current congestion levels and vessel waiting times.

4. Data Collection

For this study, we have collected data over a one-year period from 1 September 2023 to 1 September 2024. The data set we have collected initially consisted of 36,137 data values, which captured information on container vessel movements and activities across various port terminals. To ensure the accuracy and validity of the data, we undertook a thorough cleaning process. Firstly, we identified and removed #NA values which represent missing or incomplete entries in the data set. These entries might affect the reliability of the results if it was left unaddressed. Also, we handled missing values by cross-checking and inputting certain fields manually. However, there might be cases where data integrity was compromised, hence, we have opted to exclude those values entirely. After completing the data cleaning process, the final data set was reduced to 35,131 data values. It consists of information regarding container vessel movements across 254 port terminals. The data also shows how the vessel travels globally, from east-to-west and west-to-east.

5. Results and Discussion

5.1 Descriptive statistics

Total port stay time (Hours)	
Mean	39.18595542
Standard Error	0.240132735
Median	28.71666667
Mode	20.83333333
Standard Deviation	45.00871599
Sample Variance	2025.784515
Kurtosis	376.6768121
Skewness	13.76020171
Range	2070.85
Minimum	0.083333333
Maximum	2070.933333
Sum	1376641.8
Count	35131
Confidence Level(95.0%)	0.470667729

Figure 1. Descriptive statistics – Total port stay time (hours)

Total port stay time for vessels

Central tendency measures

The mean port stay time is 39.19 hours. This shows that vessels spend an average of 1.5 days at port terminals(Figure 1). The median stay time is 28.72 hours, indicating that half of the vessels spend less than this time in port. Since the median is lower than the mean, it suggests a right-skewed distribution. The most frequently occurring port stay time is 20.83 hours, which is lesser than the mean and median.

Dispersion and variability

The standard deviation for port stay time is approximately 45.01 hours, and sample variance of 2025.78 hours indicates a high variability in port stay times. This large standard deviation relative to the average port stay time highlights significant differences in how long vessels stays at the port. It also reflects the uneven distribution of vessel delays, with some vessels experiencing significantly longer port stay times than other vessels. The stay times ranges from 0.08 hours to 2070.93 hours. This extensive range underscores the presence of extreme values or outliers. Although most vessels have moderate stay times, the presence of extreme values or outliers may indicate signs of delays and congestions happening at the port. This aligns with reports highlighting port congestions happening due to ongoing geopolitical tensions (Taylor, 2024).

Distribution shape

With a skewness of 13.76 hours, the distribution is positively right skewed. This suggests that while most vessels experience relatively short stays, there are outliers with exceptionally long port stays, pulling the mean to the right.

In terms of operational efficiency, the median and mode are significantly lower than the mean which implies that majority of the vessels experience shorter port stays. The average is increased due to vessels with prolonged stays. This discrepancy highlights areas for operational improvement to reduce prolonged stays and alleviate congestion.

Anchorage Time (Hours)	
Mean	6.119784521
Standard Error	0.119180223
Median	0
Mode	0
Standard Deviation	22.33826555
Sample Variance	498.9981076
Kurtosis	78.10188059
Skewness	6.962440032
Range	504.7833333
Minimum	0
Maximum	504.7833333
Sum	214994.15
Count	35131
Confidence Level(95.0%)	0.233596993

Figure 2. Descriptive statistics – Anchorage time (hours)

Anchorage time

Central tendency measures

The mean anchorage time is approximately 6.12 hours which suggests that on average(Figure 2), container vessels spend relatively short time waiting at anchorage before being allowed to berth at the port terminal. Both median and mode have an anchorage time of 0 hours, showing that more than half of the vessels in the dataset did not spend any time waiting at anchorage, suggesting efficient berthing for a significant portion of vessels. The mean anchorage time is notably higher than both median and mode, indicating that there are a few outliers with very long anchorage duration which causes an increase to the mean.

Dispersion and variability

The standard deviation for anchorage time is 22.34 hours and a sample variance of 499 hours
shows that there is considerable variability in anchorage times, with some vessels experiencing long delays. The range of 504.78 hours highlights extreme variability in anchorage times as there are some vessels anchored for over 500 hours. This could indicate severe congestion happening or inefficiencies in port operations, where vessels are unable to dock or unload in a timely manner.

Distribution shape

With a skewness of 6.96, it shows that it is a positively skewed distribution. Additionally, kurtosis has a value of 78.10, indicating a highly peak distribution with heavy tails. This suggests that the dataset has significant outliers where a small number of vessels experiencing exceptionally longer anchorage time than majority (Figure 3).

Operation time (Hours)	
Mean	33.0661709
Standard Error	0.19994056
Median	26.5
Mode	20.83333333
Standard Deviation	37.47538983
Sample Variance	1404.404843
Kurtosis	743.2931746
Skewness	21.08408079
Range	2070.883333
Minimum	0.05
Maximum	2070.933333
Sum	1161647.65
Count	35131
Confidence Level(95.0%)	0.391889798

Figure 3. Descriptive statistics – Operation time (hours)

Operation time

Central tendency measures

The mean operation time (33.07 hours) is higher than both median (26.50 hours) and mode (20.83 hours). This shows that there are a small number of vessels experiencing significantly longer operation times, increasing the average operation time.

Dispersion and variability

The standard deviation for operation time is 37.48 hours with a sample variance of 1404.40 hours. A high standard deviation reflects a relatively widespread in operation times, showing substantial variability in operation times among vessels. The range of 2070.88 hours highlights the presence of extreme outliers in operation time.

Distribution shape

With a skewness of 21.08, it suggests a right skewed distribution with most operation times concentrated at the lower end and a few extreme values. The kurtosis value of 743.29 shows an extremely peaked distribution with heavy tails which suggests that there are many extreme values in the dataset with both very short and long operation times.

5.2 Graphical Results

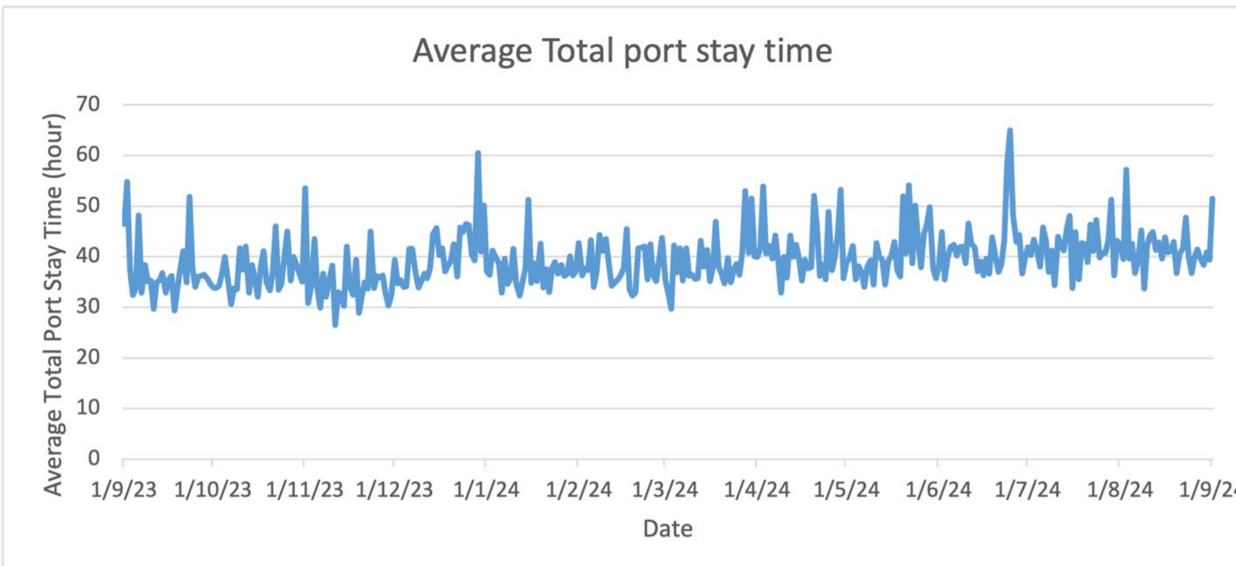

Figure 4. Average total port stay time (hours)

Total port stay time for vessels

Based on the graph shown, there are noticeable spikes in port stay time (Figure 4), particularly around mid-January 2023, end June 2023 towards early July 2024, where the time exceed 60 hours. The spikes seen in the graph may indicate seasonal or operational disruptions such as port congestions, weather conditions, or holidays. An example would be January period could correspond to new year shopping. There is a subtle upward trend that can be observed, suggesting that the average port stat time may have increased slightly over the year. This shows that ports may experience delays due to various factors such as labour shortages or increased cargo volume.

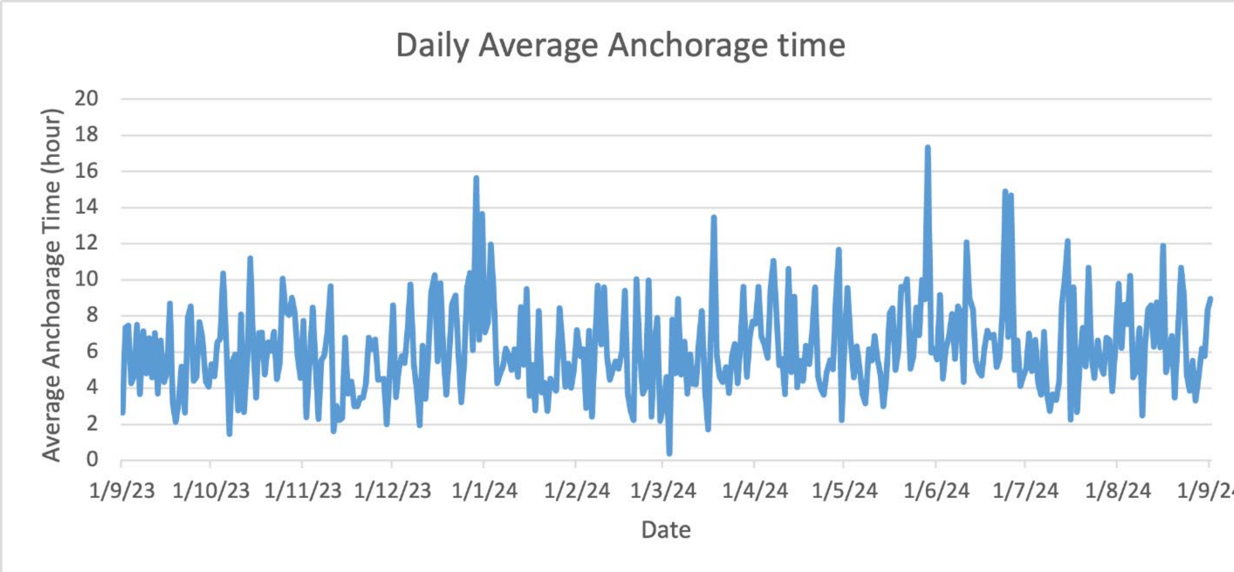

Figure 5. Average anchorage time (hours)

Anchorage time

Based on the graph, there are frequent spikes and dips, showing fluctuations in anchorage time over the year(Figure 5). In January 2024, June 2024, and July 2024, it appears to be period of higher anchorage times. Conversely, there are period of relatively low anchorage times such as October 2023, March 2024, and May 2024. The graph shows very subtle upward trend over the year that is not very apparent.

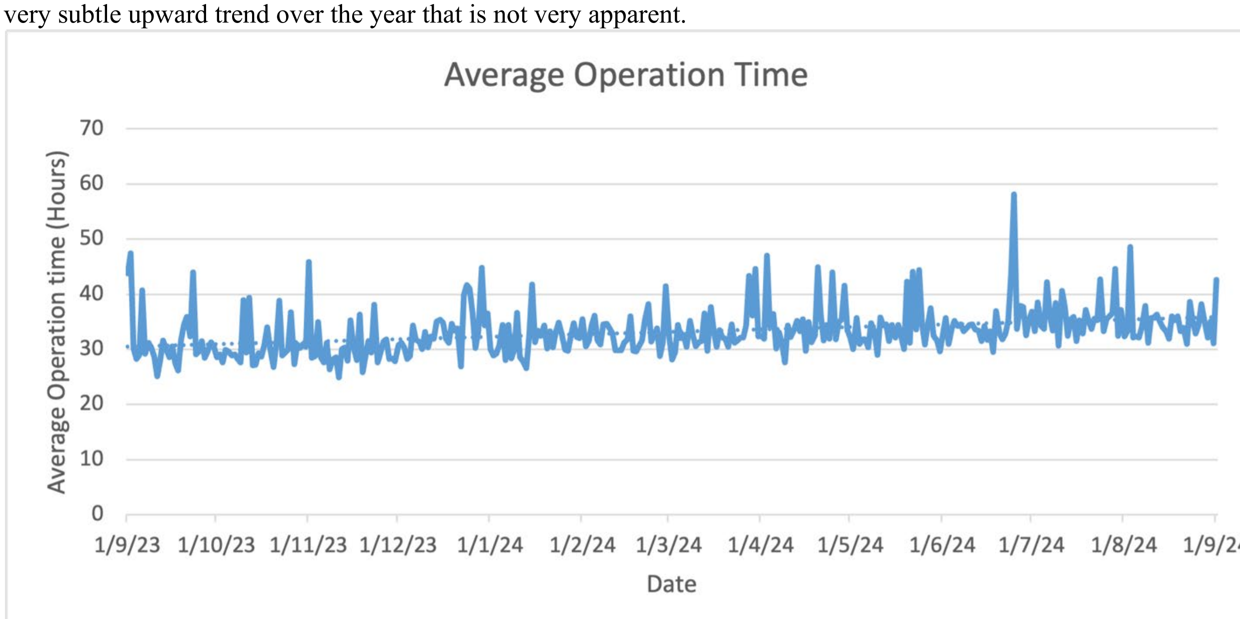

Figure 6. Average operation time (hours)

Operation time

Based on the graph (Figure 6), the average operation time shows significant variability throughout the year with frequent spikes in operation time occurring at irregular intervals, particularly in July 2024. There is no obvious seasonal pattern in the data as the fluctuations seems to appear randomly, suggesting that external factors such as operational disruptions may drive the variability.

5.3 Regression Results

SUMMARY OUTPUT - Total port stay time

Regression Statistics	
Multiple R	0.361345395
R Square	0.130570494
Adjusted R	0.128188496
Standard Er	4.986988563
Observatioı	367

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	1363.265	1363.265	54.81552001	9.23E-13
Residual	365	9077.57	24.87005		
Total	366	10440.84			

	Coefficients	*:andard Errc*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*.ower 95.0%*	*Jpper 95.0%*
Intercept	-785.721629	111.4394	-7.05066	8.96532E-12	-1004.87	-566.5777903	-1004.87	-566.578
Date	0.018192119	0.002457	7.40375	9.23197E-13	0.01336	0.023024065	0.01336	0.023024

Figure 7. Regression Analysis – Total port stay time (hours)

<u>Regression analysis</u>
R square has a value of 0.1305 which means that 13.05% of the variation in total port stay time (dependent variable, X) is explained by the date (independent variable, Y) (Figure 7). This suggests that it does not have a very strong explanatory power, however, there is still some level of interpretation of time trend in port stay durations. Next, significance F has a value of 9.23E-13. With a p-value smaller than 0.05, indicates that the regression model explains a significant portion of the variance in total port stay time, showing that the date variable is a contributing factor to port congestions happening at port terminals. Also, with 95% confidence, the true coefficient for date lies within the range. Since both bounds are positive this shows that the relationship between date and port stay time is positive. Over the study period of one year, port stay times have gradually increase. This might indicate worsening congestions or delays at port terminals over time (Figure 8).

SUMMARY OUTPUT - Anchorage time

Regression Statistics	
Multiple R	0.147467
R Square	0.021747
Adjusted R	0.019066
Standard Er	2.495789
Observatioı	367

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	50.54164013	50.54164	8.113971	0.004641
Residual	365	2273.572082	6.228965		
Total	366	2324.113722			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*.ower 95.0%*	*Jpper 95.0%*
Intercept	-152.711	55.77097993	-2.73817	0.006481	-262.383	-43.0378	-262.383	-43.0378
Date	0.003503	0.001229705	2.848503	0.004641	0.001085	0.005921	0.001085	0.005921

Figure 8. Regression Analysis – Anchorage time (hours)

<u>Regression analysis</u>
R square has a value of 0.021747 which means 2.17% of the variation in anchorage time (dependent variable, X) is explained by the date (independent variable, Y). Next, significance F has a value of 0.0046. this indicates a relatively low p-value, proving that the regression model is statistically significant. For each unit increase, the anchorage time increases by 0.0035 hours which can be translated to about 12.6 seconds. It can be accumulated overtime causing a very slight upward trend in anchorage time, if operational inefficiencies persist (Figure 9).

SUMMARY OUTPUT - Operation time

Regression Statistics	
Multiple R	0.364660814
R Square	0.132977509
Adjusted R Square	0.130602105
Standard Error	3.984626128
Observations	367

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	888.8242	888.8242	55.98101	5.52E-13
Residual	365	5795.195	15.87725		
Total	366	6684.019			

	Coefficients	*andard Errc*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-633.0110547	89.04057	-7.10924	6.18E-12	-808.108	-457.914	-808.1079603	-457.9141491
Date	0.014689299	0.001963	7.482046	5.52E-13	0.010829	0.01855	0.010828552	0.018550045

Figure 9. Regression Analysis – Operation time (hours)

<u>Regression analysis</u>
R square has a value of 0.13 which means 13% of the variation in operation time (dependent variable, X) is explained by the date (independent variable, Y). Next, significance F has a value of 5.52E-13 which is smaller than 0.05, shows that it is statistically significant. For each unit increase in date, the operation time increases by 0.0147 hours which is about 52.92 seconds. If operation time increases overtime, this may disrupt overall port efficiency such as delays in unloading and loading operations.

6. Conclusion and Future Work

This research has examined various factors contributing to port congestion, particularly focusing on vessel stay times at port terminals. The analysis revealed that the increase in total port stay time for container vessels is predominately driven by extended operation times, while the impact of anchorage times appears to be relatively minor. This observation indicated that congestion is primarily linked to the concentration of cargo operations at specific port terminals, leading to bottlenecks that causes a negative impact on handling efficiency. Moreover, the slight increase in anchorage time suggests that major container ports are prioritising berthing for large container vessels operating on key east-west trade routes, thereby facilitating efficient berthing for these vessels despite the presence of other operational inefficiencies.

Future research will concentrate specifically on vessel stay times at the Port of Singapore to unveil unique operational challenges and trends within this context. A key objective will be to compare Singapore vessel stay time patterns with the general trends identified in this study, particularly on the dominance of operation time over anchorage time. Furthermore, the study will seek to identify causes of port congestions in Singapore, including infrastructure constraints, scheduling inefficiencies, and other external disruption such as geopolitical tensions. By addressing these findings, targeted strategies will be developed to alleviate congestion. These initiatives will not only assist Singapore in tackling its port congestion issues but also offer valuable insights for other major ports striving to enhance their global competitiveness and ensuring supply chain reliability.

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