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APPLICATION OF GEOGRAPHICALLY WEIGHTED PANEL REGRESSION (GWPR) ON TUBERCULOSIS DISEASE IN NORTH SUMATRA PROVINCE

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ABSTRACT

Tuberculosis is an infectious disease caused by Mycobacterium tuberculosis and remains a serious health problem in Indonesia, particularly in North Sumatra Province. The increase in the number of cases from 2021 to 2023 indicates the need for an analytical approach that simultaneously considers spatial and temporal aspects. This study aims to apply the Geographically Weighted Panel Regression (GWPR) method to analyze the development of tuberculosis and identify the factors that significantly contribute to its spread in 33 regencies/cities in North Sumatra. Based on the results of the Chow and Hausman tests, it was found that the Fixed Effect Model (FEM) is the most suitable panel data approach to use before applying the GWPR model. The analysis shows that the three variables that most significantly influence the number of tuberculosis cases spatially are the population size, gender (male), and age ≥14 years. The application of GWPR with adaptive bisquare weighting resulted in the best model with an AIC value of 1141.567 and a coefficient of determination (R^2) of 0.99578, indicating that GWPR is a highly effective approach for analyzing the spatial spread of infectious diseases such as tuberculosis. The GWPR model is able to explain the spread of tuberculosis more accurately compared to FEM because GWPR can capture the varying influence of each variable in each region, whereas FEM only produces a single coefficient value that applies to the entire area without considering the existing spatial variations.

Keywords: Fixed Effect Model, Geographically Weighted Panel Regression, Tuberculosis.

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PRELIMINARY

Tuberculosis, induced by Mycobacterium tuberculosis, continues to pose a considerable health challenge in Indonesia, especially in North Sumatra. Tuberculosis, predominantly impacting the lungs but sometimes other organs, is transmitted through airborne droplets. Symptoms encompass persistent coughing, nocturnal perspiration, weight reduction, and pyrexia. The disease has exhibited a concerning increase in incidence over the years, with 19,147 instances in 2021, increasing to 49,999 in 2023 in North Sumatra alone. This emphasizes the necessity for a systematic strategy to comprehend and control its proliferation.

The issue of controlling tuberculosis in the region is intensified by factors such as population density, healthcare accessibility, and demographic features like age and gender. Therefore, utilizing geographically aware models such as Geographically Weighted Panel Regression (GWPR) is crucial for analyzing local changes in tuberculosis transmission patterns.

Although previous research has analyzed tuberculosis incidence rates using the GWPR method, this approach has inadequately captured the temporal and regional patterns and variations. This is particularly important in North Sumatra, distinguished by its diverse demographic, socio-economic, and geographical characteristics. Therefore, traditional methods may fail to accurately represent the spatial and temporal dynamics of tuberculosis incidence across various regions. Therefore, the GWPR technique is more suitable, as it can adapt to fluctuations in TB patterns and dynamics across various areas and temporal situations. GWPR facilitates a nuanced comprehension of TB transmission by permitting parameter estimates to fluctuate spatially and temporally, becoming it an essential instrument for devising targeted treatments and enhancing resource allocation across the region.

While prior studies have examined tuberculosis incidence rates with the GWPR method, this approach has not well represented the temporal and regional patterns and variations. This is especially significant in North Sumatra, characterized by its various demographic, socio-economic, and topographical factors. Therefore, the GWPR technique is more appropriate, as it can accommodate the variations in tuberculosis patterns and dynamics across different regions and temporal contexts. Therefore, GWPR can offer a more lucid and accurate representation of TB transmission patterns, serving as a foundation for devising more focused interventions and optimizing resource allocation throughout the region.

Prior research utilizing models like Geographically Weighted Regression (GWR) and GWPR has demonstrated that local variables, including population density, poverty rates, and healthcare facilities, substantially influence tuberculosis incidence. Angeliya et al. (2022) demonstrated that Geographically Weighted Regression (GWR) more effectively represented regional disparities in tuberculosis incidence in East Java than global models. Nabila et al. (2021) utilized Geographically Weighted Poisson Regression (GWPR) in East Kalimantan, demonstrating enhanced predictive accuracy compared to conventional panel models by accounting for regional variability in sanitation deficiencies and poverty levels. Nonetheless, despite these findings, the direct comparison between conventional panel regression models namely the Common Effect Model (CEM), Fixed Effect Model (FEM), and Random Effect Model (REM) and Geographically Weighted Panel Regression (GWPR) remains inadequately examined in the specific context of tuberculosis in North Sumatra.

These conventional models presume that predictor effects are consistent across all regions, so constraining their capacity to address spatial heterogeneity a vital consideration when examining diseases like as tuberculosis that are affected by local demographic and geographic changes. The GWPR model addresses this issue by permitting coefficients to fluctuate regionally, resulting in more precise and contextually pertinent interpretations.

Tuberculosis, caused by Mycobacterium tuberculosis, remains a significant health challenge in Indonesia, particularly in North Sumatra Province. Tuberculosis, primarily affecting the lungs but sometimes other organs, is transmitted through airborne droplets. Common symptoms include persistent coughing, night sweats, weight loss, and fever. Tuberculosis cases in North Sumatra have shown a significant increase, with a surge of 161% from 2021 to 2023. This highlights the importance of implementing spatially sensitive analytical frameworks to understand and control the spread of this disease.

The issue of controlling tuberculosis in this region is further complicated by factors such as population density, limited access to healthcare services, and demographic factors such as age and gender. Therefore, utilizing geographically aware models such as Geographically Weighted Panel Regression (GWPR) is crucial for analyzing local changes in tuberculosis transmission patterns.

METHODS

This study employs a quantitative methodology utilizing the Geographically Weighted Panel Regression (GWPR) technique to examine the dissemination of tuberculosis in North Sumatra Province. The GWPR method is applied to panel data that integrates both cross-temporal and cross-regional information, with the objective of achieving more precise parameter estimates for analyzing the determinants of tuberculosis development. The research uses secondary data sourced from the North Sumatra Provincial Health Office. The research period is from 2021 to 2023, which covers a three-year duration of tuberculosis cases in 33 districts and cities across the province.

The following are the procedures for implementing Geographically Weighted Panel Regression for tuberculosis in North Sumatra :

a. Acquiring data from research sources.
b. Perform a descriptive analysis of the variables under investigation.

c. Estimating the parameters of the regression model using panel data.
d. Choosing the optimal model via the Chow test, Hausman test, and Lagrange Multiplier test.
e. Performing checks on the assumptions of panel data regression.
f. Evaluating geographic heterogeneity.
g. Inputting Geographic Coordinate Data (Latitude and Longitude)
h. Selecting the Optimal Bandwidth Using Cross Validation (CV) Value.
i. Final Model Estimation Using Fixed Effect GWPR Methodology
j. Evaluating GWPR Model and Analyzing Results

Additionally, spatial heterogeneity was assessed using Breusch-Pagan Test before applying the GWPR model to ensure the data was appropriate for spatial analysis.

Here is a flowchart for implementing Geographically Weighted Panel Regression (GWPR) in tuberculosis cases in North Sumatra.

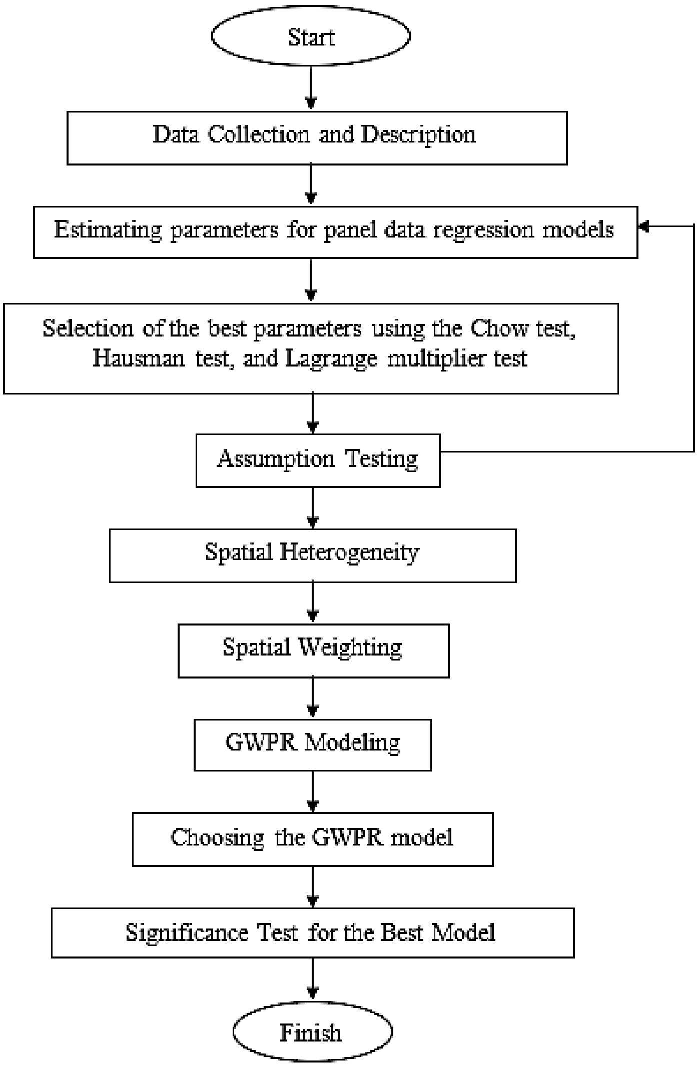

Figure 1. Research Flowchart

RESULT AND DISCUSSION

Distribution of Tuberculosis Cases in North Sumatra Province

The map below illustrates the distribution of Tuberculosis cases along with a discussion of the distribution of predictive values or coefficients for each district or city.

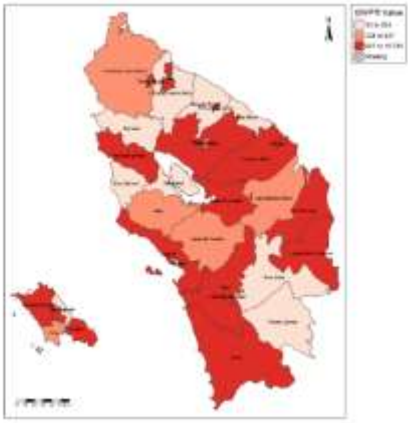

Figure 2. Distribution Map of Tuberculosis Cases in North Sumatra Province

The map above shows the distribution of tuberculosis cases in North Sumatra Province, displaying the projected number of cases for each district and city. This map categorizes regions into three categories based on value ranges: Light colors (33–324) indicate low predicted tuberculosis cases in several areas, namely: Padang Lawas, North Nias, Batu Bara, South Nias, Samosir, West Nias, Pakpak Bharat, North Padang Lawas, and North Tapanuli. Medium red (324–827) indicates moderate predictions in several areas, namely: Humbang Hasundutan, North Labuhanbatu, Nias, South Tapanuli, Toba, and Pematang Siantar. Dark red (827–15,722) indicates the highest predictions in several areas, namely: Gunungsitoli, Serdang Bedagai, Asahan, Karo, Dairi, Padangsidempuan, Medan, Langkat, South Labuhan Batu, Deli Serdang, Central Tapanuli, Labuhan Batu, Sibolga, Mandailing Natal, Tanjung Balai, Simalungun, Binjai, and Tebing Tinggi. This map confirms the spatial variation in tuberculosis prevalence in North Sumatra, which reinforces the relevance of using the GWPR method as it can capture the differing impacts of social, economic, and demographic factors on tuberculosis cases specifically at each location.

Selection Test for Panel Data Regression Models

The Chow test and the Hausman test are two statistical methodologies employed to determine the optimal estimation model in panel data regression analysis. The Chow test compares the Common Effect model with the Fixed Effect model, whereas the Hausman test distinguishes between the Fixed Effect model and the Random Effect model. Both tests assist in identifying the model that most accurately represents the investigated data.

Table 1. Chow Test and Hausman Test

Result	Conclusion	Result	Conclusion
P -Value = 0.0005185 F = 2.6779	H_0, Rejected means The best model is FEM	*P -Value* = 0.02259 F = 16.29	H_0, Rejected means The best model is FEM

The Chow Test yielded a p-value of 0.0005185 and an F-value of 2.6779. Due to the p-value being less than 0.05, the null hypothesis is rejected, signifying that the Fixed Effect Model (FEM) is more suitable than the Common Effect Model (CEM). This signifies considerable disparities among districts and cities in North Sumatra, rendering the Fixed Effect Model more suitable. The Hausman test findings indicate a p-value of 0.02259 and an F-value of 16.29. Due to the p-value being less than 0.05, the null hypothesis is once again rejected, indicating that the Fixed Effect Model (FEM) is more suitable than the Random Effect Model (REM). This signifies that the individual effects among observation units are associated with the independent variable. Consequently, according to both assessments, the Fixed Effect Model is the most suitable model for examining the impact of numerous factors on the incidence of Tuberculosis cases in North Sumatra.

Classic Assumptions Test for Panel Data Regression

The multicollinearity assessment utilizing the Variance Inflation Factor (VIF) is presented in the table below.

Table 2. Multicollinearity Test

Variable	VIF
X_3	9.8
X_{4b}	1.11
X_{5a}	3.75

The multicollinearity test findings indicate that the Variance Inflation Factor (VIF) for the variable Number of Medical Personnel is 9.8, approaching the common threshold of 10, signifying a moderate to high level of multicollinearity, while still acceptable. The variable Gender - Female has a VIF value of 1.11, while the variable Age ≤14 Years has a VIF value of 3.75, indicating the absence of multicollinearity concerns, as their values are much below the threshold. This panel regression model does not exhibit significant multicollinearity difficulties; however, the variable Number of Medical Personnel requires ongoing scrutiny due to its potential impact on the stability of the model's results.

Autocorrelation Test

The autocorrelation test yielded a p-value of 0.9535, significantly exceeding the 0.05 significance threshold. This signifies that the null hypothesis is not rejected, leading to the conclusion that there is no autocorrelation in the employed panel regression model. This indicates that the model's residuals do not exhibit a recurring pattern or systematic temporal association, hence satisfying the requirement of no autocorrelation.

Heteroscedasticity Test

The heteroscedasticity test findings indicate a p-value of 0.03803, which is below 0.05, signifying the rejection of the null hypothesis and the presence of heteroscedasticity in the data distribution. The assumption of homoscedasticity is violated, perhaps due to regional characteristic disparities that result in non-constant error variation. The succeeding study will employ the Geographically Weighted Panel Regression (GWPR) approach to solve this issue and account for spatial influence.

Geographically Weighted Panel Regression (GWPR)

The selection of optimal weights for the GWPR modeling occurs subsequent to the heteroscedasticity test indicating spatial data variation. The subsequent stage is to ascertain the optimal bandwidth and the inter-district/city distances in North Sumatra Province prior to the construction of the weighting matrix. The distance between districts or cities is determined using the Euclidean formula.

Euclidean distance is used in this research because it represents the straight-line distance between two geographical points (such as the center of a district or city) on a two-dimensional plane. This method is commonly used in spatial analysis due to its simplicity and its ability to capture the geographical proximity between regions. In the context of GWPR, this distance measurement is used to determine how close or far a region is from another region, which directly affects the weight assigned to each observation in the local regression calculation.

The selection of bandwidth plays a very important role in the GWPR model because it determines the extent of the local area used to estimate the model parameters at each location. A bandwidth that is too narrow can produce overly localized estimates and lose the general pattern, while a bandwidth that is too wide can overlook important local variations. In this study, the selection of optimal bandwidth is based on the lowest AIC value to obtain the most suitable model while remaining sensitive to local variations.

Nias Regency (u_1, v_1) and Mandailing Natal Regency (u_2, v_2).

$$d_{ij} = \sqrt{\left(u_i - u_j\right)^2 + \left(v_i - v_j\right)^2}$$

$$= \sqrt{(97.7417 - 99.3673)^2 + (1.08694 - 0.74324)^2}$$
$$= \sqrt{(-1.6256)^2 + (0.3437)^2}$$
$$= \sqrt{2.64258 + 0.11813}$$
$$= \sqrt{2.76071}$$
$$= 1.661537$$

North Sumatra Province comprises 33 regencies and municipalities. The created matrix for assessing the links between districts and cities will measure 33x33, based on the current distances. Subsequently, AIC is employed to determine the optimal bandwidth. The Adaptive Bisquare weighting function yielded the lowest AIC value among the kernel functions evaluated in this study, hence being selected as the optimal weighting function. The outcomes of the optimal bandwidth selection are presented in the table below.

Table 3. Weight of Kernel Function

Kernel Weight Function	AIC	R^2
Adaptive Bissquare	1141.567	0.995781
Adaptive Gaussian	1230.452	0.9861768
Adaptive Exponential	1215.24	0.9883691

The assessment of the three kernel weight functions employed in Geographically Weighted Panel Regression (GWPR) modeling indicates that the Adaptive Bisquare function produces the most favorable outcomes. The lowest AIC value of 1141.567 and the highest R^2 value of 0.995781 imply a superior model fit to the data. In comparison, the Adaptive Gaussian function produces a higher AIC of 1230.452 and a lower R^2 of 0.9861768, but the Adaptive Exponential has an AIC of 1215.24 and a R^2 of 0.9883691. According to the model selection criteria of reducing AIC and maximizing R^2, the Adaptive Bisquare weighting function is the superior option for GWPR analysis in this study. The estimation results and parameter significance tests for Toba Regency and Karo Regency are presented in the subsequent table.

Table 4. Parameter Significance Test

Variable	Toba		Karo	
	Parameter	*P-Value*	Parameter	*P-Value*
X_1	-7.64E-03	0.778	-1.14E-02	0.411
X_{4a}	1.55140082	0.04	1.4380906	0.023
X_{5b}	0.20487617	0.648	0.1005576	0.742

The findings of parameter estimation and significance testing in Toba Regency and Karo Regency indicate that several variables influence the incidence of tuberculosis cases. In Toba Regency, the variables of population size and individuals aged 14 years or younger are not statistically significant. Conversely, the male gender variable has a substantial positive effect (parameter = 1.5514; p-value = 0.04), suggesting that an increase in the male population correlates with a rise in tuberculosis cases. In Karo Regency, the male gender variable exhibits a positive and significant effect (parameter = 1.4381; p-value = 0.023), suggesting a correlation between the male population and an increased incidence of tuberculosis cases. Nonetheless, the factors of population size and individuals aged 14 years or younger are not significant in Karo Regency. This suggests that the population size and the percentage of individuals over 14 years old do not significantly affect the transmission of tuberculosis in both districts, however the male gender consistently exerts a substantial influence.

In summary, the outcomes of the parametric significance test at a significance level of 0.05 indicate that districts and cities in North Sumatra Province can be categorized according to the variables affecting the incidence of tuberculosis cases.

Table 5. Significance of GWPR Model Parameters

Research Variables	District/City with Significant Influence ($p < 0.05$)
X_1 (Population Count)	Simalungun, Deli Serdang, Serdang Bedagai, Pematangsiantar, Tebing Tinggi
X_{4a} (Male)	Nias, Mandailing Natal, Tapanuli Selatan, Tapanuli Tengah, Tapanuli Utara, Toba, Labuhan Batu, Asahan, Simalungun, Dairi, Karo, Deli Serdang, Langkat, Nias Selatan, Humbang Hasundutan, Pakpak Bharat, Batu Bara, Labuhanbatu Selatan, Labuhanbatu Utara, Nias Utara, Nias Barat, Sibolga, Tanjungbalai, Medan, Binjai, Padangsidimpuan, and Gunungsitoli.
X_{5b} (Age $\geq$ 14 Years)	Labuhan Batu, Simalungun, Deli Serdang, Langkat, Samosir, Serdang Bedagai, Batu Bara, Padang Lawas, Padang Lawas Utara, Labuhanbatu Selatan, Labuhanbatu Utara, Pematangsiantar, Tebing Tinggi, Medan, and Binjai

The use of the Geographically Weighted Panel Regression (GWPR) model to analyze tuberculosis in North Sumatra Province reveals substantial spatial variability, with each component affecting the incidence of tuberculosis cases. Numerous areas and cities, like Nias, Mandailing Natal, and Tapanuli Selatan, exhibit a pronounced impact of the male gender variable on the dissemination of tuberculosis. Certain regions, like Simalungun, Deli Serdang, and Tebing Tinggi, exhibit a substantial correlation with the population variable, affecting the dissemination of tuberculosis. Furthermore, regencies and cities such as Labuhan Batu, Simalungun, and Medan are significantly affected by the age variable of 14 years or older. It was determined that several regencies, such Simalungun and Deli Serdang, are affected by all three elements, but certain regions are influenced by only one or two variables, and regencies such as Padang Lawas exhibit no significant influence. This pattern indicates that the distribution of tuberculosis in North Sumatra is spatially heterogeneous, and the GWPR approach effectively identifies the variations in the effects of these factors across different regions.

The results of this study, using the Geographically Weighted Panel Regression (GWPR) model, indicate significant spatial variation in the factors influencing tuberculosis incidence across North Sumatra. Specifically, the population size, gender (male), and age ≥14 years were identified as the most significant determinants of tuberculosis cases in different districts and cities. The application of GWPR has shown that these factors have different impacts depending on the region, which is consistent with the existing literature that emphasizes the importance of local demographic and socio-economic characteristics in tuberculosis transmission (Angeliya et al., 2022; Nabila et al., 2021).

This finding supports the argument made by Angeliya et al. (2022) who found that regional disparities in tuberculosis incidence are better represented through geographically weighted models than global models. In this study, the population size variable, for instance, showed significant effects in districts like Simalungun, Deli Serdang, and Tebing Tinggi, which align with the findings of previous research highlighting the role of urbanization and population density in tuberculosis spread. Similarly, the male gender variable was significant in areas like Nias, Mandailing Natal, and Tapanuli, which further supports the findings of Nabila et al. (2021), who observed that gender-specific factors often correlate with disease incidence in certain regions.

However, this study also extends previous research by including a spatially explicit analysis of tuberculosis transmission, showing that factors influencing tuberculosis are not uniformly distributed across regions. The use of GWPR allowed for the identification of spatial heterogeneity, a feature often overlooked in studies applying conventional panel data methods like Fixed Effect or Random Effect Models. This spatial dimension adds nuance to our understanding, demonstrating that traditional methods may fail to capture the localized variations in tuberculosis transmission, as shown by the results of the Chow and Hausman tests which confirmed the necessity of a Fixed Effect Model for this context.

In terms of policy implications, the findings of this study offer valuable insights for local health authorities and policymakers. The ability of GWPR to identify spatially varying effects means that interventions can be more targeted, addressing the specific needs of each district based on their unique demographic, socio-economic, and geographical characteristics. For instance, areas with higher population density might benefit from increased healthcare resources or public health campaigns to raise awareness, while regions with higher male tuberculosis cases could focus on gender-specific outreach programs.

Additionally, policymakers can use these findings to optimize resource allocation by prioritizing districts with higher tuberculosis incidences and more significant spatial variations. This research underscores the importance of adopting spatially sensitive approaches in public health planning, where tailored interventions based on local data can result in more effective control measures and improved health outcomes.

By identifying specific factors that influence tuberculosis transmission in different regions, the study complements the existing body of literature and provides a more granular understanding of the disease's dynamics. This contributes to the growing body of evidence supporting the need for geographically informed public health policies

CONCLUSION

Research using the Geographically Weighted Panel Regression (GWPR) method concludes that this model is effective for analyzing the spread of tuberculosis in North Sumatra Province. The results of the Chow and Hausman tests indicate that the Fixed Effect Model (FEM) is the most appropriate method before applying the GWPR model. The three characteristics that most influence the spatial spread of tuberculosis are the population size, the male gender, and the age of 14 years or older. The application of GWPR with adaptive bisquare weighting produced the best model, marked by an AIC value of 1141.567 and a coefficient of determination (R^2) of 0.99578, indicating that the GWPR model is capable of explaining almost all the variation in tuberculosis spread in the studied region. The GWPR approach is an excellent tool for evaluating the spatial distribution of infectious diseases, including tuberculosis, while still considering local variations in disease transmission.

These findings are not only relevant to the context of tuberculosis in North Sumatra but also open up opportunities for the application of GWPR in other studies involving spatial aspects. Therefore, further research is recommended to apply this method in other regions or on other infectious diseases, particularly those influenced by geographical, demographic, and healthcare access differences. Additionally, further model development can be carried out by incorporating seasonal data or real-time data when available, thereby enabling more dynamic spatial analysis and supporting decision-making in the field of public health. (Syamsualam & Hidayat, 2022)

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