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Original Article

Modelling Freight Transportation Distribution for Food Security based on Equlibrium Consumption (Case Study in West Java, Indonesia)

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Abstract *- The rice distribution systems in West Java are under constant stress because of changing production capacity and rising demand for consumption. This study examines interregional rice movement by creating a gravity model based on equilibrium consumption that directly connects areas of surplus and deficit production through spatial interaction processes. Freight flows are estimated by utilizing population size as a proxy for consumption demand, while integrating production capacity and distance resistance, which are calibrated via regression analysis. The analysis starts with multiple linear regression to find the main factors that cause trips to happen. Then, it uses an iterative gravity calibration process to make sure that flows between the starting and ending regions are balanced. The results show that population growth has a strong positive effect on rice movement, while economic growth has a weak negative effect, which is likely due to changes in eating habits and preferences. At a Level of Service value of 0.62, the model reaches equilibrium with an estimated flow of about 44000 tons. This is still less than the observed distribution volume of about 60000 tons. This difference shows that transportation factors only slightly limit rice distribution in West Java. Instead, it is mainly supported by strong demand and strong links between supply chains in different regions. Overall, the equilibrium consumption-based gravity model demonstrates stronger explanatory performance than conventional gravity approaches and provides a more reliable foundation for improving distribution efficiency and supporting regional food security planning.*

Keywords *- Distribution, Equilibrium Consumption, Freight Transportation, Food Security, Gravity Model.*

1. Introduction

Increasing demand for freight transportation has played a vital role in defending the regional logistic network and strengthening national food security [1-3]. Land transportation is still the first choice in Indonesia for the distribution of agricultural products from production areas to places where they are consumed. This mode of transportation is more popular because of its greater flexibility, easier access, and lower cost compared to other transportation options [4, 5]. The distribution patterns of commodities are primarily determined by the interactions between major production centers and regions with high consumption levels [5-7]. According to the Central Bureau of Statistics, Indonesia produced 53.14 million tons (GKG) of rice statewide in 2024. The volume of rice produced for domestic use fell from 31.10 million tons in 2023 to 30.62 million tons, showing that production capacity is steadily decreasing. This downward trend shows that changes in the amount of cultivated land, yield variability, and climate-related stressors are still limiting agricultural performance and overall output levels of production [8-10].

Rice is Indonesia's main food and helps keep the country politically stable, socially cohesive, and economically stable [8, 11, 12]. West Java Province is one of Indonesia's main rice-growing areas. In 2024, it is expected to make 8.62 million tons of GKG, which is about 4.98 million tons of milled rice. Indramayu, Subang, and Karawang are the two most important places for getting food to people in the country. They are also important places for getting food to people. Because these areas are strategically important, rice must flow smoothly from surplus zones to deficit regions to ensure quick delivery and cost-effective distribution [13].

The distribution of rice throughout West Java is constantly hampered by structural issues brought on by frequent traffic jams, a lack of transportation capacity, and a lack of coordination between supply and demand trends. When combined, these interconnected factors raise logistical costs and extend delivery times throughout the distribution network [9, 14]. These challenges worsen the gap between supply and demand, result in inefficient resource allocation, and cause price volatility, shortages in some areas, and surplus accumulation in others [15]. As population expansion continues to increase overall consumption demand, these factors pose a growing threat to national food security [16, 17]. Imbalanced rice distribution in West Java causes commodity movements to diverge from local consumption needs, leading to shortages in certain areas and surplus accumulation in others. Because market forces primarily govern production and distribution decisions, logistics flows often develop without considering economic efficiency or the distinct consumption demands of each region.

This research proposes a data-driven approach to improve rice distribution in West Java using a gravity-based model that examines interregional flows by combining accessibility, consumption demand, and production capacity. The model follows rice movement from surplus-producing regions such as Indramayu, Karawang, and Subang toward deficit consumption areas, including Bandung, Bekasi, and Depok, to clarify spatial distribution behavior. This spatial mapping is intended to limit inefficiencies within the logistics network while ensuring a stable and uninterrupted flow of rice throughout the province. Efficient rice circulation contributes to livelihood security, regional economic stability, and the reliability of the logistics system. The consumption-based analytical framework offers empirical guidance for policy actions designed to reduce regional imbalance, maintain price stability, optimize infrastructure allocation, and enhance overall distribution performance.

2. Related Works

Ongoing gaps between surplus-producing regions and deficit areas remain a key issue in assessing logistics performance and regional food security. These imbalances go beyond simple differences between supply and demand and instead point to structural inefficiencies shaped by infrastructure quality, economic capacity, and geographic limitations. Growing empirical findings show that variations in production capability, network accessibility, and consumption behavior actively drive inefficiencies in the movement of staple commodities, particularly essential goods such as rice. According to Miao et al. [18], it is difficult for locations with surplus production to efficiently route their supply to locations with shortages because food commodities are sensitive to distance-related constraints. This study emphasizes that in order to replicate spatial interdependence among regions, production conditions and consumption data must be integrated.

As gravity-based models mathematically connect production levels, consumer demand, and resistance related to distance into a single analytical framework, they are frequently used to explain patterns of commodity movement. Zhao et al. [19] demonstrate that distance decay and spatial impedance remain the main determinants of freight mobility, even when the gravity modeling framework incorporates socioeconomic traits and geographic isolation to more precisely predict truck origin-destination movements.

With an improved deep gravity model for heavy-truck flows, Yang [20] advanced freight modeling by extending gravity-based approaches to capture nonlinear spatial behavior within distribution systems. Subsequent theoretical work by Capoani [21] examined gravity modeling concepts and emphasized the shift from traditional formulations toward more flexible representations that accommodate heterogeneous spatial structures. In addition to these theoretical contributions, Abdullah [22] confirmed the robustness of gravity models for representing commodity flows along regional transport corridors using Malaysian freight data. Chen [23] made further enhanced gravity formulations through improved treatment of fixed effects, which increased their applicability to complex spatial and panel datasets.

Previous studies have not included the variable of rice production commodities in the coverage zone framework, so that population has been the only determining factor in distribution analysis. In a production and consumption-based equilibrium approach in each coverage zone, the supply and demand for rice commodities should be optimized through a supply chain model that is appropriate to the characteristics of the region.

The novelty of this study is reflected in its effort to balance surplus rice-producing zones with deficit regions through the application of a gravity-based framework. This approach exploits interzonal movement patterns without reliance on Unconstrained Gravity Model parameters, allowing deficit areas to satisfy consumption demand through the most efficient distribution distances from surplus zones.

3. Materials and Methods

3.1. Research Design

This study applies a quantitative approach using a gravity-based modeling framework to represent the attraction forces governing rice distribution for food security objectives.

3.2. Variables

The dependent variable in this research is the volume of goods flow between zones, the amount of rice moved from surplus to deficit areas. The independent variables are population size, used as a stand-in for consumption demand, Rice production at the district/city level, land use area, and the Gross Regional Domestic Product (GRDP) for each city in West Java Province.

3.3. Research Area

This study focuses on West Java Province, a significant region for rice production and consumption in Indonesia. It analyzes the movement of rice between surplus and deficit areas. Indramayu, Karawang, and Subang are the main rice-producing areas, while Bandung, Bekasi, and Depok are large cities with high demand due to high population density. This study is limited to official city and regency boundaries. The research map area can be seen in Figure 1.

Fig. 1 Map of the research area

3.4. Data Collection

The Central Bureau of Statistics (BPS) and other government agencies provided secondary data for this study. Land use records were used to quantify agricultural area, and rice production estimates at the district and city levels were combined with demographic data to indicate population size. To represent the true travel distance, intercity distances were calculated using Google Maps. An Origin-Destination matrix that depicts possible rice flow patterns throughout the province was made possible by the integration of these variables.

3.5. Research Procedure

The research began with the acquisition and processing of secondary institutional data to define essential variables, including the origin-destination matrix Tij, the interzonal cost matrix Cij, and total goods generation Oi and attraction Dj. Model robustness was ensured by calibrating a logarithmically transformed gravity formulation using multiple linear regression to estimate the friction parameter γ. The ideal origin-destination matrix Tij model was obtained by iteratively balancing the unconstrained gravity model in equilibrium simulations using these calibrated coefficients. As shown in Figure 2, a systematic framework was used to implement the whole methodical process.

3.5.1. Literature Review

The first steps involve collecting and analyzing scientific data on the division of production and consumption zones, supply and demand equilibrium models, gravity-based methods, and the dynamics of commodity distribution. The objectives of this study are to establish a theoretical framework, find research gaps, and create an analytical framework relevant to model creation.

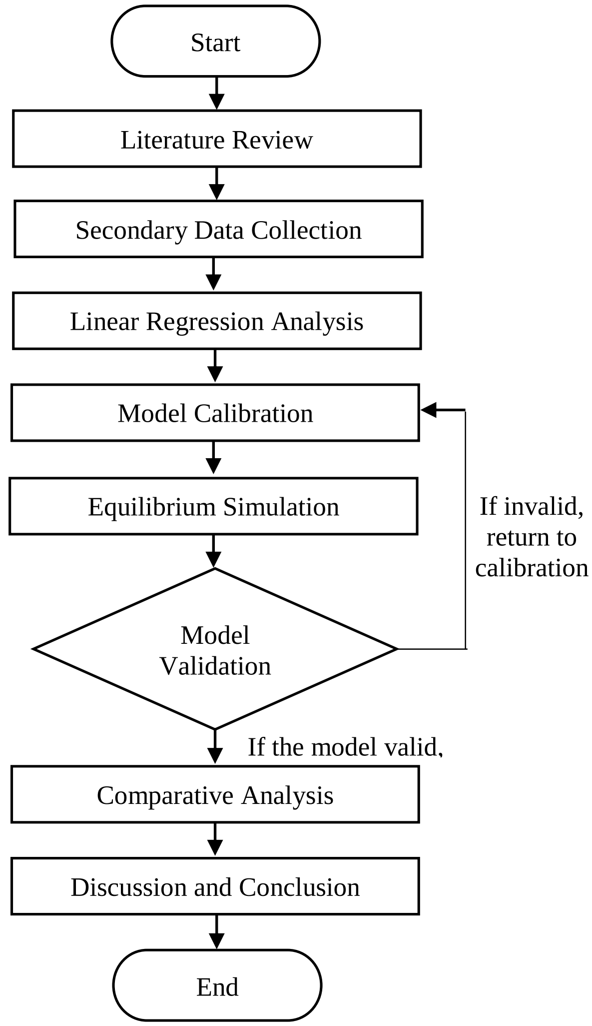


Fig. 2 Flowchart of the research

3.5.2. Secondary Data Collection

Using secondary data from Central Berau Statistics and pertinent technical organizations, this study builds a rice distribution model. The Gross Regional Domestic Product is used to represent regional economic conditions, while district and city-level rice production population estimates are used as a stand-in for consumption demand and land use area. Each zone's production capacity is represented by the size of agricultural land, and the resistance factor in the modeling structure is the interzonal distance, which is calculated using Google Maps to reflect the real travel distance.

3.5.3. Linear Regression Analysis

The first analytical stage in determining the statistical significance of production qualities, population number, land extent, and associated factors' effects on product generation and attraction is linear regression. The variables that are kept for the next development of the gravity model are chosen based on the assessment's findings.

3.5.4. Model Calibration

The trip resistance parameter γ, which represents interregional logistics friction, is estimated during the calibration phase using multiple linear regression within a gravity modeling framework. The goal of this procedure is to identify an impedance specification that most accurately represents the resistance features affecting commodity flows between zones. The power form impedance function is chosen for further simulations based on calibration performance since it offers a more accurate representation than other functional structures.

3.5.5. Equilibrium Simulation

The degree of service and the equilibrium between supply and demand under both current circumstances and optimal distribution scenarios were assessed through equilibrium simulations.

3.5.6. Model Validation

In order to verify that the model is consistent with observed conditions, residual normality, statistical significance, and distance distribution behavior are evaluated. The process goes back to the calibration stage for more improvement if these conditions are not met.

3.5.7. Comparative Analysis

In order to assess differences between simulated outputs and observed distribution flows and gauge the effectiveness of the current rice distribution network, comparative analysis is utilized.

3.6. Data Analysis

Generation refers to the total number of trips originating from a particular zone (Oi), while attraction represents the number of trips directed to all destination regions (Dd) within the research area.

3.6.1. Generation and Atraction Movement

Both the volume of trips originating from a particular land use or zone and the volume of trips drawn toward other land uses or zones are estimated by the modeling stages of movement generation and attraction. [24]. This process is illustrated schematically in Figure 3.

Figure 3 illustrates the generation and attraction movement process. Based on a zone's features, the Travel Generation Model forecasts how many trips will be made [25]. Travel generation refers to the quantity of movements originating from the Origin zone (Oi), while travel attraction refers to the number of trips directed to the Destination zone (Dd) within the research area. Trip production is another term for the total number of trips leaving an origin zone.

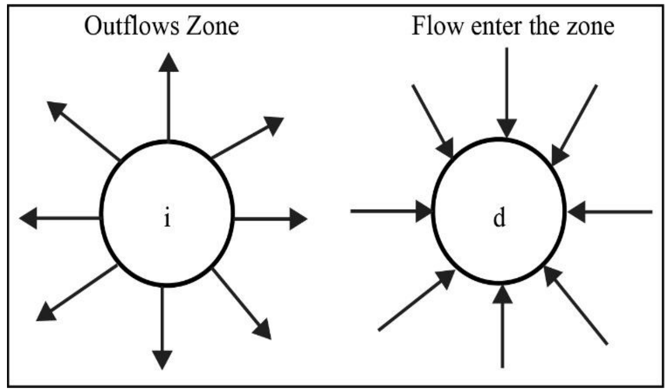


Fig. 3 Generation and Attraction freight

2. Based on the kind of commodity being transported, the gravity model for freight transportation modeling offers a mathematical formula to calculate the total volume of freight moved between two locations. The general expression of the freight transportation volume between origin and destination zones is presented in Equation (1).

$$T_{idk} = \frac{S_{ik} D_{dk} f_{id}}{\sum D_{dk} f_{id}} \quad (1)$$

Where:

T_{idk} = the amount of k commodities produced in zone i and shipped to destination zone d.

S_{ik} = Total quantity of freight shipped from the i zone

D_{dk} = the overall level of demand in the d zone for k commodities

f_{id}= barriers factor/the friction (= 1 / didλ)

λ = parameter

This model makes use of Newton's concept of gravity, which was derived from the gravity law analogy in Equation (2).

$$F_{id} = G\frac{m_i m_d}{d_{id}^2} \quad (2)$$

G is the movement attraction's gravitational constant, and accessibility metrics include cost, duration, or distance. The GR model is developed as follows for transportation purposes in Equation (3).

$$T_{id} = k\frac{O_i O_d}{d_{id}^2} \quad (3)$$

Where k is a constant. The Gravity Model can be expressed mathematically in Equation (4).

$$T_{id} = O_i D_d A_i B_d f(C_{id}) \quad (4)$$

4. Results and Discussion

4.1. Modelling Trip Generation

Trip generation analysis for rice commodities was conducted employing multiple linear regression within the following equation model:

$$y = -1370 + 0.991\,X1 + 0.0682\,X2 \qquad (5)$$

Where X_1 represents the agricultural land area (ha) and X_2 denotes rice production volume (tons). Estimation outcomes show that land area exerts a positive and statistically significant influence on trip generation, indicating that zones with wider cultivation tend to generate larger outbound rice flows as a result of higher production capacity. Rice production volume also displays a positive coefficient but lacks statistical significance, which is likely explained by multicollinearity with land area since both variables are structurally interrelated.

The model exhibits strong goodness of fit with an R^2 of 0.93, an adjusted R^2 of 0.93, and a predicted R^2 of 0.89, confirming high explanatory capability alongside reliable predictive accuracy. The results further indicate that the population variable was excluded from the final formulation because it did not provide a statistically meaningful contribution to the. This finding aligns with the observations of Sundram et al. [26], who identified income-related consumption diversification as a moderating factor in staple food logistics across ASEAN economies. Normality test for multiple linear regression can be seen in Figure 4.

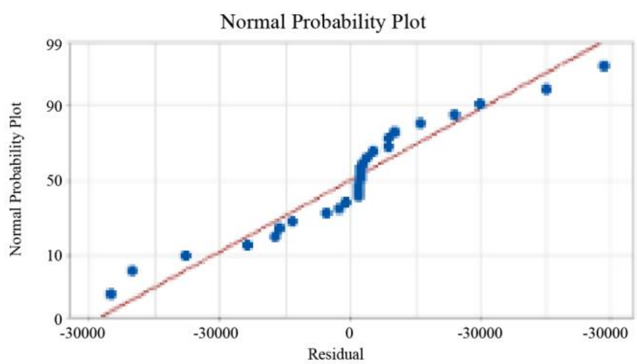


Fig. 4 Normal probability plot multiple regression of rice commodity

Figure 4 illustrates the residual normality test for the trip generation regression model using a Normal Probability Plot. There are very few deviations from normality, as seen by the distribution of residual points closely following the diagonal reference line. It appears from this visual pattern that the residuals exhibit an approximately normal distribution. The regression diagnostics, which show no systematic pattern or extreme skewness in the plotted residuals, provide additional evidence in favor of the normalcy assumption.

The overall distribution shape is not distorted by the relatively large standardized residuals of a few observations. As a result, the classical linear regression model's normalcy requirement is adequately satisfied. The regression model used to estimate trip generation (Oi) can be regarded as statistically appropriate and trustworthy for subsequent use in equilibrium simulation and model calibration within the gravity-based analytical framework once this assumption has been verified.

MATLAB can be used to visualize the distribution of rice in West Java Province thanks to the simulation results. Every city or district is represented as a circle, with the size of each representing the demand for or availability of rice. Disparities in rice distribution between districts are reflected in size differences. Whereas smaller circles denote lower levels, larger ones highlight regions with higher production or demand. This graphic explains spatial inequality and identifies planning and resource allocation priorities. A simulation of the rice commodity distribution model for the inter-regional zoning of West Java is shown in Figure 5.

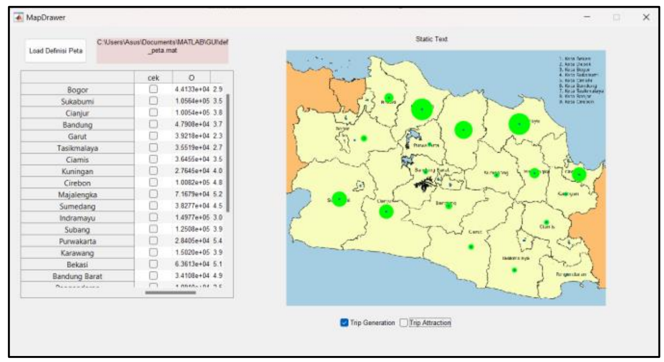


Fig. 5 Simulation model of rice commodity generation in actual conditions

With the same approach, the rice commodity movement model in West Java Province is simulated through computational programming as presented in Figure 6. The figure illustrates the estimation of origin and destination flows in rice distribution, where certain zones act as surplus production areas while others represent regions with high consumption or trade activities. The rise and pull characteristics of rice movement highlight the role of production centers as key suppliers and the dependency of deficit regions on these supply zones.

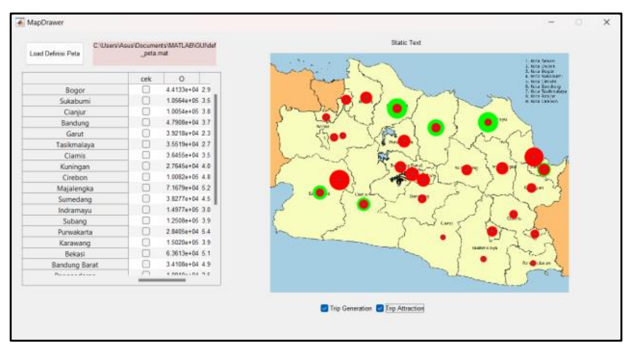


Fig. 6 Comparison of the generation (rise) and attraction (pull) in simulation models of rice commodity movement under actual conditions

The results of the simulation of rice distribution movements in West Java Province are visualized spatially using MATLAB. The major rice-producing regions are shown in Figure 6 as green circles and include Indramayu, Subang, Karawang, and Purwakarta. The logistical difficulties facing

Indonesia are reflected in this spatial imbalance, with northern districts acting as surplus centers that supply southern consumption centers [27].

To verify the suitability of the distribution pattern with actual conditions, the analysis was redone using a gravity model approach. This stage aimed to determine the extent to which the model was able to reproduce the empirical distribution pattern of rice commodities and to review the relationship between production and consumption areas.

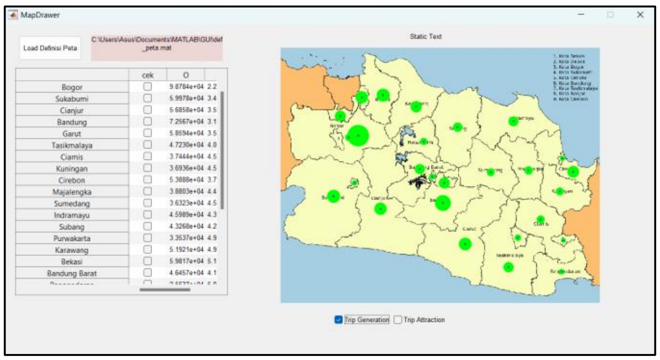


Fig. 7 Simulation model of rice commodity generation in the model gravity condition

Figure 7 presents the simulation results of the rice trip generation model derived from the gravity-based approach. The green colors on the map indicate the main producing areas with higher trip generation rates, which illustrate the potential for rice distribution movements in each district/city. The distribution of these generation values is influenced by regional production and supply capacity factors, so that areas with high rice production, such as in northern and central West Java, appear more dominant.

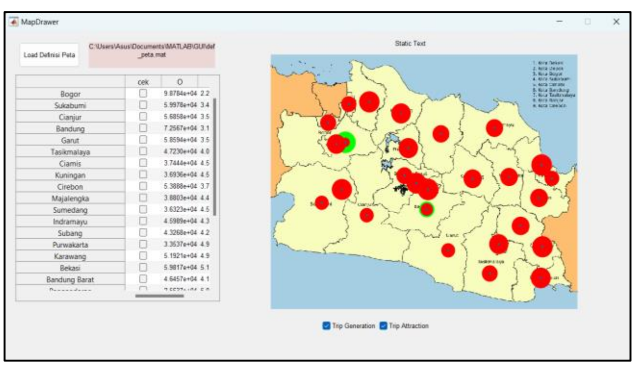


Fig. 8 Comparison of the generation (rise) and attraction (pull) in simulation models of rice commodity movement under model conditions

Figure 8 shows a comparison between supply and demand in the gravity model calibration conditions. Red coloring shows the degree of rice demand at each location, while the spatial distribution of data points depicts the equilibrium between production and consumption regions. Demand centers cluster in densely inhabited areas, according to simulation results, which show interaction patterns that match real distribution behavior. Wang et al. and Leitão used calibrated gravity models to ensure rice flows adhere to equilibrium distribution principles and spatial interaction mechanisms [28, 29]. Distributions from the resulting flow simulations closely matched observations from the field.

4.2. Trip Movement Distribution

The generation and attraction method allows rice distribution patterns to be simulated based on the commodity matrix. Table 1 presents the application of various impedance functions in the gravity model to estimate rice flows between regions. The results indicate that the power impedance formulation performs best, showing that it most accurately captures resistance influences on rice distribution in West Java Province.

Table 1. Unlimited gravity modeling calibration

Function Obstacle	Calibration of Model Parameters		
	B	**A**	**β**
Power	-0.9111	17.8371	0.91112
Negative Exponential	-1.7408×10^{-6}	6.9744	1.7408×10^{-6}
Tanner	-19049×10^{-6}	5.6895	19049×10^{-6}

The power impedance function is:

$$f(Cid) = A \times e^{\beta Cid} \quad (6)$$

The power impedance function in Table 1 is the best way to show how hard it is to move rice in West Java. The estimated parameters show that flow intensity and distance are related in the opposite way, meaning that the farther away the rice has to travel, the less likely it is to be delivered.

The power function is more stable numerically and has consistent calibration across all zones than the Tanner and exponential forms. These findings underscore the efficacy of the power-based model as a reliable tool for analyzing regional logistics and goods distribution in West Java [25, 27].

The rice distribution network is depicted by the red line, which runs throughout West Java Province from important production hubs to consumption locations. Areas of high-volume rice transportation are indicated by the thick line, especially from the agricultural zones in the north to the heavily populated urban centers and non-producing districts in central and southern West Java.

This graphic demonstrates how interdependent the regions are and how important the main rice-producing regions are to maintaining regional food security. The outcomes of the rice distribution model simulation within the intra-provincial zone of West Java are presented in Figure 9.

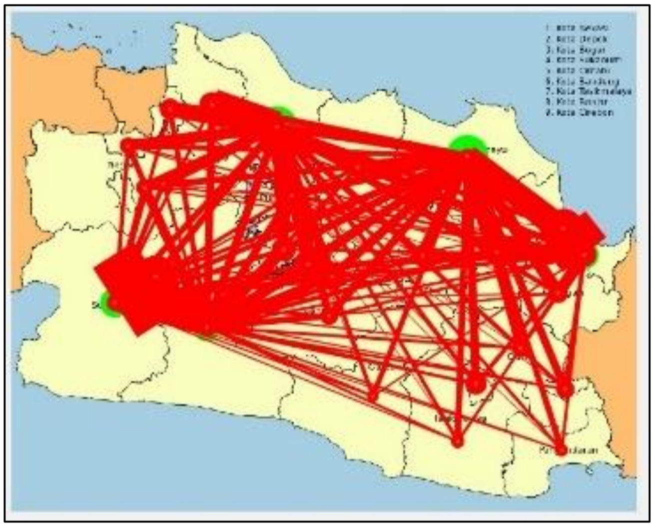


Fig. 9 Desireline model of rice commodity distribution in actual conditions

Figure 9 shows a map of the rice distribution network in West Java Province. This map illustrates regional interactions through the flow of rice shipments and receipts under actual conditions. Red lines indicate distribution routes between districts and cities. Greater thickness and density of lines show higher levels of distribution activity. This pattern shows that regions with large production and consumption centers are connected through a complex and dense distribution network, especially in the central and eastern parts of the province.

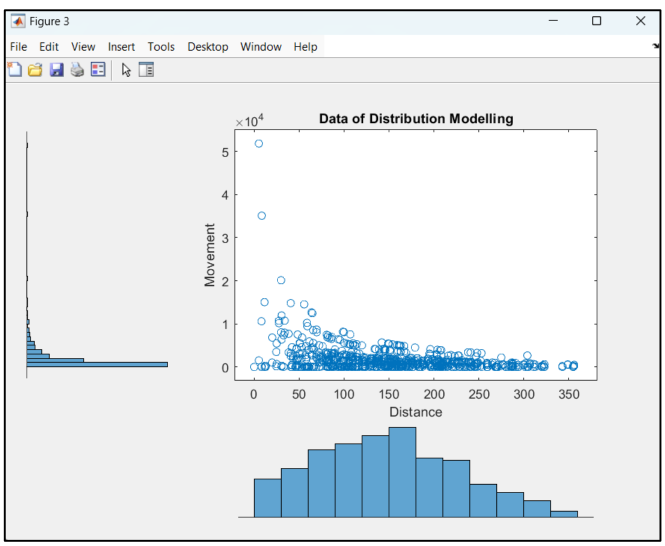
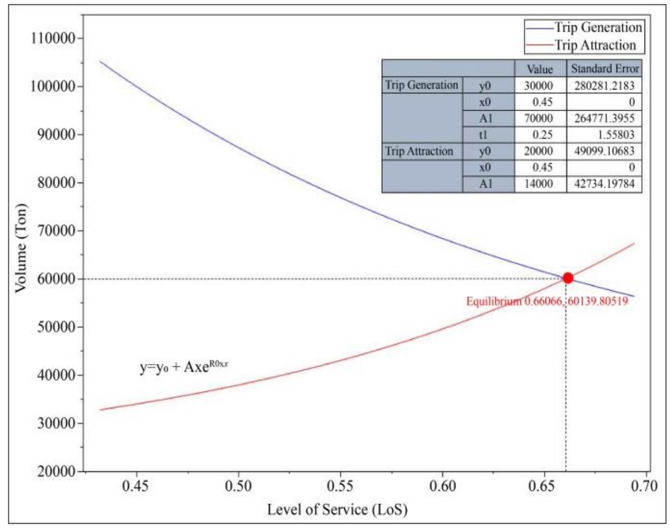


Fig. 10 Distribution distance of rice commodity distribution in actual condition

Figure 10 shows the distribution distance of rice commodity under actual conditions. Most rice movements occur within short to medium distances, while flows decline sharply as distance increases. This verifies an *exponential decay* relationship, where longer travel distances reduce movement intensity consistent with spatial interaction theory.



		Value	Standard Error
Trip Generation	y0	30000	280281.2183
	x0	0.45	0
	A1	70000	264771.3955
	t1	0.25	1.55803
Trip Attraction	y0	20000	49099.10683
	x0	0.45	0
	A1	14000	42734.19784

Fig. 11 Equilibrium model consumption curves for rice commodity under the current condition

Figure 11 shows the relationship between Level of Service (LoS) and the volume of generation and demand for rice commodities modeled using a power function. The blue curve represents a decrease in generation (exponential decay), while the red curve shows an increase in pull (exponential growth), in accordance with the theory of spatial interaction, which states that an increase in travel resistance will decrease generation but increase pull to the destination area.

The estimated parameters show different base values and time constants, where the pull function is more sensitive to changes in LoS than generation. The intersection point of the two curves at LoS = 0.66066 with a flow volume of 60,139 tons indicates the equilibrium condition of the distribution system.

This relatively high LoS value indicates that the rice distribution system is resilient to increases in travel resistance, so that the logistics flow remains stable because it is influenced by basic needs and inter-regional supply chain linkages. Studies on rice and seed logistics networks across Indonesian provinces emphasize the critical role of spatial accessibility and infrastructure connectivity in sustaining stable interregional commodity flows [13, 30].

Figure 12 presents a spatial representation of equilibrium conditions, illustrating how freight flows are distributed across regions once the gravity model has attained equilibrium.

Figure 12 shows the desireline model under gravity model conditions. This figure illustrates the simulated flow of goods connecting production and consumption areas, based on calibrated resistance parameters. The highest network density is found in the northern and central regions. This pattern reflects what has been observed empirically.

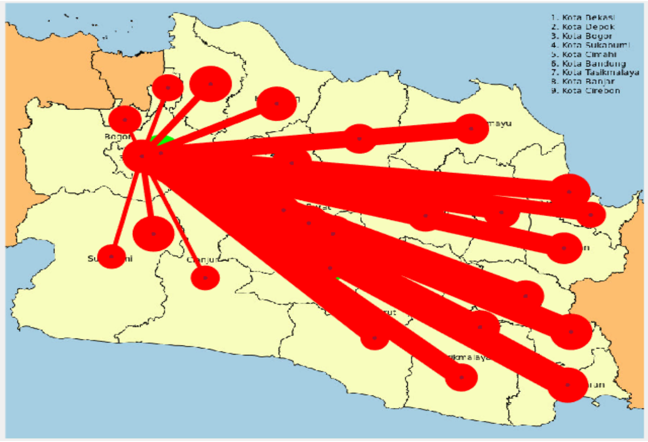


Fig. 12 Desireline model of rice commodity distribution in the gravity model condition

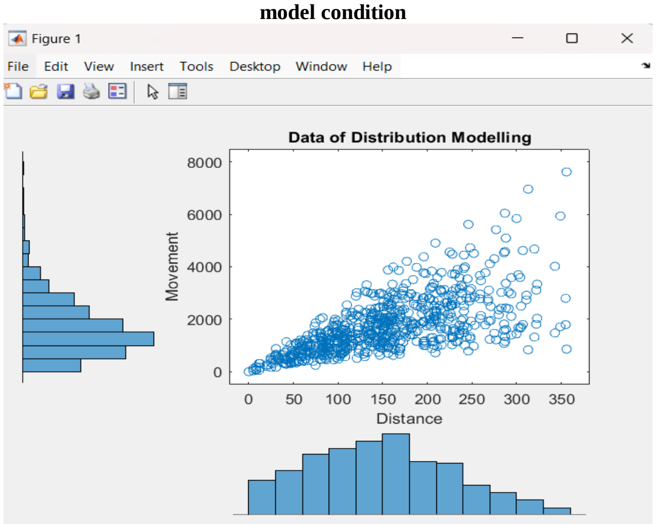


Fig. 13 Distribution distance of rice commodity distribution in the gravity model condition

Figure 13 illustrates the distance distribution under gravity model conditions. The simulated flow exhibits an exponential decrease pattern with distance, confirming the model's validity in describing the effect of resistance on rice movement.

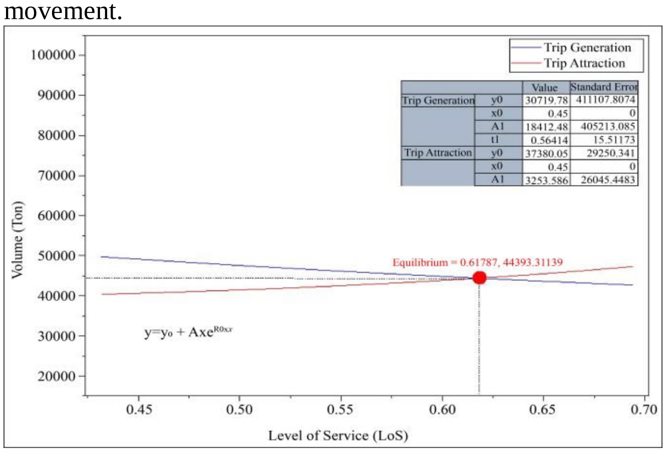


Fig. 14 Equilibrium model consumption curves for Rice Commodity under the optimized condition

Figure 14: The relationship between the production volume and attractiveness of rice commodities and the Level of Service (LoS) metric of transportation quality and efficiency is depicted in Figure 14. An exponential function is used to model this relationship. The gravity model predicts equilibrium at LoS = 0.61787 with a volume of 44,393 tons. These results imply that the gravity model considerably underestimates the real system performance because the anticipated equilibrium value is lower than the observed data. The pattern that appears when logistical flows persist despite increasing transportation constraints indicates that the distribution of rice in West Java is rather inelastic to travel constraints. This strength stems from strong interregional supply chain links, which are reinforced by rice's vital position in the food system. The distribution network sustains constant interregional mobility in spite of shifting operational demands and transportation circumstances [31, 32]. Merkus [33] suggests that future research should encourage the use of composite impedance variables in gravity-based modeling frameworks to describe the quality and dependability of journey time infrastructure. This development is anticipated to improve forecast accuracy and provide a more accurate depiction of intricate logistics system dynamics.

The equilibrium consumption-based gravity approach delivers stronger explanatory and predictive performance than many gravity-based freight models reported in recent studies that rely mainly on population size or economic scale as attraction variables. By directly accounting for surplus and deficit production conditions and calibrating distance resistance through empirical estimation, the model is able to reproduce interregional rice flows more accurately as reflected in high R^2 and predicted R^2 values. This approach generates spatial interaction patterns that better reflect observed distribution behavior than earlier unconstrained gravity formulations. The use of MATLAB-based computational techniques further enhances the analysis by accelerating iterative optimization, supporting stable equilibrium convergence, and improving the reliability of interzonal interaction assessment.

5. Conclusion

This study examines rice distribution in West Java by employing trip generation modeling, spatial interaction assessment, and gravity-based equilibrium simulation. The results of the regression show that the size of agricultural land has the biggest effect on rice trip generation, while the amount of rice produced has a smaller but still positive effect. These results show that spatial production capacity has a bigger effect on distribution intensity than the total output quantity.

Spatial simulation results show that rice distribution flows are mostly in the north and center, where Indramayu, Subang, Karawang, and Purwakarta are the main production hubs. Demand intensity rises as they move south and east. The gravity-based framework accurately replicates this pattern, illustrating that interregional rice movement is influenced by transport resistance, production capacity, and consumption demand.

The estimated findings show that when compared to field observations, the model tends to underestimate flow values. This condition can be caused by a variety of factors, such as incomplete flow determinant variables, linearity assumptions that fail to effectively reflect spatial linkages, and variability between regions that is not represented in the model structure. In order to get around these restrictions, further validation was done by assessing prediction stability using cross-validation tests, examining error distribution patterns, and assessing model suitability using residual analysis. Despite the underestimation bias, the validation process showed that the model structure remained consistent and was able to represent the main trends in inter-zone interaction patterns, so that the model could still be used with careful interpretation and potential for development through the addition of variables or model transformation in subsequent studies.

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