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Supply Chain Distribution Cost Optimization Using the Transportation Model (Vogel's Approximation Method and Modified Distribution Method)

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Abstract

Distribution costs remain a major concern in supply chain management, yet comparative evidence on transportation allocation methods across business settings remains fragmented. This study compared initial solutions generated by the North-West Corner (NWC), Least Cost, and Vogel's Approximation Method (VAM) and examined optimality assessments using the Modified Distribution Method (MODI) and Stepping Stone method. A descriptive-comparative quantitative approach was applied to secondary data on transportation costs and allocations reported in published logistics and manufacturing case studies. The analysis compared initial transportation costs and reported optimization outcomes across methods. At UKM Rajawali Kaca, VAM yielded a distribution cost of IDR 180,200, compared with IDR 181,900 using Least Cost and IDR 229,500 using NWC. At Pabrik Tahu Dompyong Wetan, VAM and NWC produced identical costs of IDR 196,000. At PT Tirta Utama Abadi, optimization reduced the reported distribution cost for November 2025 from IDR 21,794,083 to IDR 19,331,108. These findings suggest that VAM can provide a competitive initial allocation, although its advantage is context-dependent and subsequent optimality assessment remains necessary to establish minimum transportation costs. The study provides comparative evidence to inform distribution planning and highlights opportunities to extend transportation models by incorporating vehicle capacity constraints and demand variability.

Keywords: Cost Optimization; Supply Chain Distribution; Transportation Model; Vogel's Approximation Method; Modified Distribution Method

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INTRODUCTION

Distribution is one of the largest and least controllable cost components in a firm's operations, especially for firms that must serve several markets from several supply points. Poorly planned allocations raise transportation costs without improving service. Several Indonesian studies describe the same pattern across different industries. Deliveries at a bottled-water distributor were allocated by drivers' habits rather than by measured cost efficiency (Widia & Nuratri, 2026). At a glass distributor, shipping followed the preferences of the drivers, which left distribution costs uncontrolled (Mubarok & Juliandara, 2025) . At a courier company, distribution planning directly shaped operating cost (Al Zaqi Sembiring et al., 2022) . The pressure has grown with fuel prices, because the 2022 Pertalite increase of about 30% raised transport cost per unit and forced distributors to re-plan their allocations. For small and medium enterprises with thin margins, such as tofu producers, even small savings per trip matter (Hasibuan et al., 2026).

This study argues that distribution cost should be treated as a decision problem to be solved with a formal model, not as a by-product of routine delivery habits. The transportation model, a special case of linear programming, allocates goods from several sources to several destinations at minimum total cost, subject to supply and demand constraints (Irvana Arofah & Nianty Nandasari Gesthantiara, 2021a) . Solving it has two stages. An initial feasible solution is built first, then tested and improved until no unused route can lower the cost. The first stage alone is not sufficient. Initial methods such as North West Corner (NWC), Least Cost, and Vogel's Approximation Method (VAM) differ in whether and how they use cost information, so they do not guarantee a minimum (Hasibuan et al., 2026a). The theoretical and practical case for the study is that a firm needs both a feasible allocation and evidence that the allocation cannot be improved.

Previous studies support this approach but differ in scope. (Dimasuharto et al., 2021) compared NWC, Least Cost, and VAM for glass distribution and verified the best result with Stepping Stone, which gave Rp180,200 under VAM against Rp229,500 under NWC. (Ermawati, 2021) found VAM slightly better than Least Cost for seaweed distribution (Rp1,709,250,000 against Rp1,713,300,000) and confirmed the result with MODI. (Widia & Nuratri, 2026) paired VAM with MODI at a mineral-water distributor and reported savings of 11.30% and 15.20% in two consecutive months. Arofah and Gesthantiara (2021) used all three initial methods with both optimality tests, supported by QM for Windows, in a shoe-

distribution case. (Al Zaqi Sembiring et al., 2022) found that NWC and VAM gave identical costs for a courier network and extended the analysis with an assignment model for driver wages. (Syaputri & Nafia, 2025) applied VAM and MODI to cost data projected for 2025, and (Hasibuan et al., 2026a) re-analysed secondary data from an earlier tofu-distribution study.

Read together, these studies leave four gaps. First, most apply only one or two initial methods, or one optimality test, so the choice of method is rarely justified by a systematic comparison. Second, several rely on secondary or projected data rather than current operational data from the firm (Hasibuan et al., 2026a; Syaputri & Nafia, 2025) . Third, the networks are small, often two or three sources, and unbalanced cases that require a dummy source or destination are interpreted only superficially. Fourth, sensitivity to changes in unit cost is seldom analysed, although fuel prices change often.Announce such an analysis but do not report it. Non-cost factors, such as driver wages, vehicle capacity, and delivery time, are acknowledged as limitations in several studies (Al Zaqi Sembiring et al., 2022; Syaputri & Nafia, 2025) but are rarely tested.

Acknowledged as limitations in studies(Dewanti, 2024),It compares NWC, Least Cost, and VAM on the same primary dataset from. It verifies the resulting allocations with both Stepping Stone and MODI, so the optimality conclusion does not rest on a single test. It also adds a sensitivity analysis of unit transport cost and an explicit treatment of the supply–demand imbalance. The theoretical foundation is the linear-programming transportation model, which minimizes $Z = \Sigma\Sigma\ CijXij$ subject to supply and demand constraints and non-negative flows. Optimality is judged by opportunity cost under Stepping Stone and by the potential values ($Cij = Ui + Vj$) and improvement indices under MODI (Taha, 2019; Yunistira & Ibnas, 2014).

Accordingly, this study aims to analyse the current distribution pattern and cost to compare the initial solutions produced by the North West Corner, Least Cost, and Vogel's Approximation methods, and to test and improve them with the Stepping Stone and Modified Distribution methods in order to determine the minimum-cost allocation. It also aims to assess how sensitive that allocation is to changes in unit transport cost, and to estimate the cost saving relative to the current practice, so that the findings can guide distribution decisions in comparable small and medium-sized firms.

METHODS

This study employed a quantitative approach using a descriptive-comparative design to examine the effectiveness of transportation optimization methods in minimizing supply chain distribution costs. The analysis focused on distribution cost data reported in published case studies involving manufacturing, logistics, and distribution companies. A comparative approach was considered appropriate because it allowed the performance of different transportation methods to be examined across business settings while accounting for differences in distribution networks and operational costs. The transportation problem was formulated as a linear programming model involving multiple supply points and destinations, with the objective of identifying cost-efficient allocations under supply and demand constraints (Mushalifah et al., 2024). The data consisted of reported transportation costs, initial allocation results, and optimal distribution costs obtained from previous studies. Comparisons were conducted within individual cases to avoid treating differences in transportation costs across companies as direct measures of methodological performance. This approach draws on the transportation optimization framework applied by Arofah and Gesthantiara (2021), particularly the comparison of feasible initial solutions and subsequent optimality assessment.

The analysis involved three initial allocation methods: North-West Corner (NWC), Least Cost, and Vogel's Approximation Method (VAM). NWC determines the initial allocation based on supply and demand positions without considering transportation costs, whereas Least Cost prioritizes routes with the lowest unit transportation costs. VAM incorporates penalty calculations based on differences between the two lowest costs in each row and column to identify potentially more efficient allocations (Askerbeyli, 2020). The transportation model was expressed as $\mathbf{Z = \Sigma_i \Sigma_j c_{ij} x_{ij}\ (1)}$, subject to $\mathbf{\Sigma_j x_{ij} = s_i,\ \Sigma_i x_{ij} = d_j,}$ $\mathbf{and\ x_{ij} \geq 0\ (2)}$, where Z represents total transportation cost, c_{ij} denotes the unit transportation cost from source i to destination j, x_{ij} represents the allocated quantity, and s_i and d_j indicate supply and demand, respectively. Where necessary, dummy sources or destinations were considered to balance differences between total supply and demand. The initial solutions were compared based on their reported total transportation costs, with lower costs indicating more efficient initial allocations within the same distribution network.

The optimality of transportation allocations was examined through the Modified Distribution Method (MODI) and Stepping Stone procedures reported in the selected

studies. MODI evaluates unoccupied transportation routes using the improvement index $\mathbf{K_{ij} = c_{ij} - u_i - v_j}$ **(3)**, where u_i and v_j represent row and column potentials. A feasible allocation is considered optimal when all improvement indices are nonnegative for a cost-minimization problem. The Stepping Stone method similarly evaluates potential cost changes through closed-loop allocation adjustments (Dimasuharto et al., 2021). The analysis compared initial transportation costs with reported optimal costs and, where baseline operational costs were available, evaluated cost efficiency using $\mathbf{Cost\ Savings\ (\%) = [(C_0 - C_1)/C_0] \times 100}$ **(4)**, where C_0 represents the baseline distribution cost and C_1 denotes the optimized cost. The findings were interpreted descriptively to identify differences in method performance, the consistency of optimality results, and their implications for distribution planning. The analysis was limited to the transportation costs and allocation outcomes available in the reviewed cases, without incorporating additional operational constraints such as delivery time windows, heterogeneous vehicle capacities, or uncertain demand.

RESULTS

1. Comparison of Initial Transportation Cost Solutions

The comparative analysis of transportation cost optimization methods revealed differences in the initial allocation costs generated by the North-West Corner (NWC), Least Cost, and Vogel's Approximation Method (VAM). The results were drawn from published distribution case studies involving manufacturing enterprises, logistics services, and other distribution operations. Each method was evaluated according to its ability to produce a feasible allocation while minimizing transportation expenditures within the supply and demand constraints of the respective distribution network.

The results showed that VAM produced the lowest reported initial transportation cost or an equivalent minimum-cost solution in the cases examined. At Pabrik Tahu Dompyong Wetan, both NWC and VAM generated an initial distribution cost of IDR 196,000, while Least Cost produced a higher cost of IDR 206,800 (Hasibuan et al., 2026). A similar result was observed in the J&T Express distribution network, where NWC and VAM generated identical initial costs of IDR 5,859,200 (Sembiring et al., 2022). For CV Manurindo, VAM produced an allocation cost of IDR 1,709,250,000, slightly lower than the IDR 1,713,300,000 obtained using Least Cost (Ermawati, 2021). A more pronounced difference emerged in the analysis of UKM Rajawali Kaca dan Aluminium, where VAM generated an

initial cost of IDR 180,200, compared with IDR 181,900 using Least Cost and IDR 229,500 using NWC (Dimasuharto et al., 2021). The transportation costs reported for these cases are summarized in Table 1.

Table 1. Comparison of Transportation Costs Across Initial Allocation Methods

Company/Entity	NWC (IDR)	Least Cost (IDR)	VAM (IDR)	Reported optimal cost (IDR)
Pabrik Tahu Dompyong Wetan	196,000	206,800	196,000	196,000
J&T Express	5,859,200	—	5,859,200	5,859,200
CV Manurindo	—	1,713,300,000	1,709,250,000	1,709,250,000
UKM Rajawali Kaca	229,500	181,900	180,200	180,200

Note. A dash indicates that the corresponding result was not available in the source data. Costs represent different distribution networks and should be compared within each company rather than directly across companies.

Table 1 demonstrates that the relative performance of initial allocation methods varied according to the transportation network being examined. VAM achieved the lowest reported cost in the UKM Rajawali Kaca and CV Manurindo cases, whereas its results were identical to NWC in the Pabrik Tahu Dompyong Wetan and J&T Express cases. The largest difference among the reported initial solutions occurred at UKM Rajawali Kaca, where the NWC allocation exceeded the VAM solution by IDR 49,300. Meanwhile, the difference between Least Cost and VAM was only IDR 1,700. In the CV Manurindo case, VAM reduced the initial allocation cost by IDR 4,050,000 relative to Least Cost. These findings illustrate that the selection of an initial allocation procedure can influence the resulting transportation cost, although a lower initial cost does not independently establish global optimality.

2. Relative Cost Differences Between Transportation Methods

The initial transportation costs were further examined by expressing the difference between each method's allocation cost and the reported optimal cost as a percentage. This comparison provides a more meaningful interpretation of relative method performance because the companies operate at substantially different distribution cost scales. The percentage differences are illustrated in Figure 1.

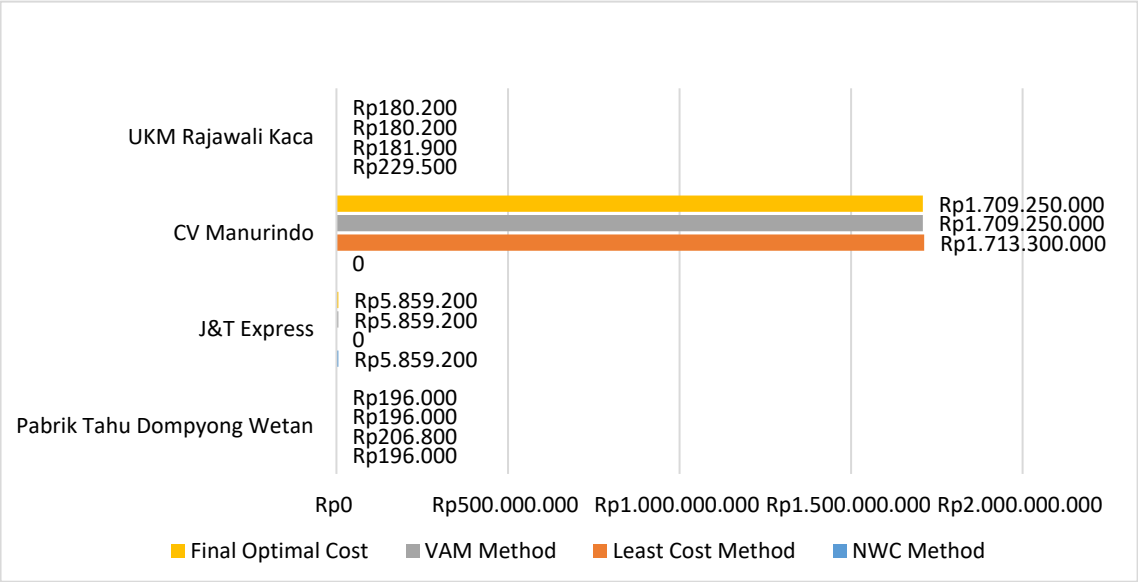


Figure 1. Percentage Excess of Initial Transportation Costs Over the Reported Optimal Cost

Figure 1 illustrates that the NWC solution for UKM Rajawali Kaca was 27.36% higher than its reported optimal transportation cost, representing the largest relative difference among the available comparisons. The Least Cost solution exceeded the reported optimum by 0.94% in the same case. At Pabrik Tahu Dompyong Wetan, Least Cost produced an allocation cost 5.51% above the reported optimum, whereas NWC and VAM achieved identical minimum reported costs. For CV Manurindo, the difference between Least Cost and the reported optimum was approximately 0.24%. Both NWC and VAM matched the reported optimal transportation cost in the J&T Express case. The figure indicates that VAM provided a competitive initial solution across the available comparisons, while the relative disadvantages of NWC and Least Cost depended on the structure of each transportation problem.

3. Transportation Cost Optimization and Operational Savings

The application of optimality testing procedures provided further evidence regarding potential reductions in transportation expenditure. The transportation models considered in the selected studies used MODI or Stepping Stone to assess whether the initial allocation could be improved. These procedures evaluate the cost implications of introducing previously unused distribution routes and adjusting allocations while maintaining supply and demand feasibility.

A notable example was reported for PT Tirta Utama Abadi, where the application of VAM and MODI reduced distribution costs during November and December 2025 (Widia & Nuratri, 2026). The reported operational costs and optimized allocation costs for both periods are presented in Table 2.

Table 2. Comparison of Actual and Optimized Transportation Costs at PT Tirta Utama Abadi

Period	Actual cost (IDR)	Optimized cost (IDR)	Cost savings (IDR)	Savings (%)
November 2025	21,794,083	19,331,108	2,462,975	11.30
December 2025	20,803,010	17,640,728	3,162,282	15.20

Source: Calculated from the reported transportation costs in Widia and Nuratri (2026).

As presented in Table 2, the optimized transportation allocation reduced the November 2025 distribution cost by IDR 2,462,975, equivalent to 11.30% of the actual expenditure. A larger reduction was recorded in December 2025, when the optimized allocation lowered distribution costs by IDR 3,162,282, representing a 15.20% saving. These results demonstrate that improvements in transportation allocation can generate measurable financial benefits when evaluated against an existing operational cost baseline. The differences between the two periods also suggest that the potential savings depend on the distribution conditions represented in each monthly dataset. The reported savings therefore describe this particular company and should not be interpreted as an average efficiency rate applicable to all enterprises included in the comparative analysis.

Evidence from another transportation optimization case showed that Wira Shoes obtained a reported optimal transportation cost of IDR 8,400,000 using QM for Windows software (Arofah & Gesthantiara, 2021). This result illustrates the use of computational tools to support transportation problem solving. However, the available comparative summary did not provide the full allocation matrix or an independent recalculation of this result. Consequently, the reported optimal costs are treated as outcomes documented in the respective source studies rather than as newly verified solutions obtained through a common computational procedure.

4. Mathematical Interpretation and Additional Distribution Findings

The transportation optimization results were interpreted using the linear programming objective function introduced in Equation (1) of the Methods section. The model minimizes total transportation expenditure by selecting shipment quantities that

satisfy the supply and demand constraints specified in Equation (2). For the MODI method, the row and column potentials are determined from the occupied cells of a feasible transportation solution according to the following relationship:

$$c_{ij} = u_i + v_j \quad (5)$$

where c_{ij} represents the unit transportation cost associated with an occupied route, while u_i and v_j denote the corresponding row and column potentials. One potential is assigned a value of zero to establish the remaining potentials. The resulting values are subsequently used to calculate the improvement indices defined in Equation (3). For a cost-minimization problem, a feasible solution is optimal when all reduced costs for unoccupied cells are nonnegative. This condition provides the mathematical basis for determining whether reallocating shipments to an unused route could further reduce the total transportation cost.

Additional findings highlight operational considerations that are not fully represented by transportation cost minimization alone. In the J&T Express case, the reported driver wage cost obtained through an assignment model was IDR 713,499, compared with IDR 1,185,333 associated with the distribution routes obtained through the NWC and VAM solutions (Sembiring et al., 2022). The difference of IDR 471,834 indicates that optimizing shipment allocation and optimizing personnel assignments can produce different cost outcomes because they address distinct operational decisions. These results suggest that transportation allocation alone may not capture all components of distribution expenditure.

Supply and demand imbalances were also observed in the projected medical device distribution case examined by Syaputri and Nafia (2025). Total demand reached 24,719 boxes, while available supply amounted to 23,125 boxes, resulting in a shortage of 1,594 boxes. A dummy source representing this difference was therefore required to balance the transportation model. The study also reported a VAM transportation cost of IDR 271,004,184. The dummy allocation should be interpreted as a mathematical representation of unmet demand rather than actual shipments originating from an additional warehouse. This distinction is important because balancing the transportation matrix makes the optimization procedure mathematically feasible without resolving the underlying operational shortage.

Overall, the comparative findings indicate that VAM frequently produced favorable initial allocation costs and, in several reported cases, matched the optimal transportation

costs obtained after further evaluation. The results also demonstrate that transportation optimization can generate measurable savings when actual operational costs are available for comparison. Nevertheless, the magnitude of potential savings varies across distribution networks, and the reported outcomes do not establish that a particular initial allocation method will always outperform alternative procedures. The operational examples further highlight the importance of considering personnel costs, supply shortages, and other practical constraints when translating mathematical solutions into distribution decisions.

DISCUSSION

The findings of this study demonstrate that transportation optimization methods can support more efficient distribution decisions, although their performance varies across operational settings. The comparative results presented in Table 1 indicate that Vogel's Approximation Method (VAM) generally produced competitive initial transportation costs relative to the North-West Corner (NWC) and Least Cost methods. The differences were particularly evident in distribution networks where the selection of shipping routes substantially influenced total transportation expenditure. At UKM Rajawali Kaca dan Aluminium, VAM generated an initial cost of IDR 180,200, compared with IDR 181,900 using Least Cost and IDR 229,500 using NWC. The 27.36% difference between the NWC allocation and the reported optimal cost illustrates the financial consequences of selecting routes without adequately considering their transportation costs. Dimasuharto et al. (2021) reported a similar pattern, showing that VAM provided the lowest initial transportation cost in the glass distribution network, which was subsequently confirmed through Stepping Stone analysis. These findings suggest that incorporating cost considerations into the initial allocation process can reduce the need for subsequent adjustments and provide a more efficient starting point for distribution planning.

The relative performance of the three methods can be explained by differences in their allocation procedures. NWC determines shipment quantities according to the position of cells within the transportation matrix, without explicitly considering transportation costs. Least Cost prioritizes the available route with the lowest unit cost, while VAM considers the difference between the two lowest costs in each row or column before determining an allocation. This penalty-based procedure provides information about the potential cost consequences of not selecting a particular route. The results from Pabrik Tahu Dompyong

Wetan demonstrate that selecting the lowest available unit cost does not necessarily produce the lowest total transportation cost. In this case, Least Cost generated an initial allocation cost of IDR 206,800, exceeding the IDR 196,000 obtained using both NWC and VAM. Hasibuan et al. (2026) similarly examined transportation allocation methods in tofu distribution and emphasized the importance of comparing initial solutions before undertaking further optimization. The findings also reveal that VAM does not invariably outperform other methods. At J&T Express, NWC and VAM produced identical transportation costs of IDR 5,859,200, as reported by Sembiring et al. (2022). This result indicates that different allocation procedures may produce equivalent solutions depending on the structure of the cost matrix and the distribution of supply and demand.

The distinction between obtaining an initial feasible solution and establishing an optimal allocation is particularly important when interpreting these findings. Although VAM frequently generated favorable initial costs, its results should not be regarded as globally optimal without further evaluation. The Modified Distribution Method (MODI) and Stepping Stone procedures provide an additional assessment by examining whether unused transportation routes could reduce total expenditure. MODI evaluates improvement indices derived from row and column potentials, while Stepping Stone assesses potential cost changes through closed-loop allocation adjustments. Arofah and Gesthantiara (2021) demonstrated the relevance of combining initial allocation methods with optimality testing in their analysis of Wira Shoes, which produced a minimum reported transportation cost of IDR 8,400,000. The findings of Dimasuharto et al. (2021) also showed that the VAM solution for glass distribution remained unchanged following the Stepping Stone optimality assessment. These studies support the use of a sequential optimization procedure in which initial allocations are evaluated before being adopted as final distribution decisions. The present comparison reinforces this methodological distinction, although the optimality conclusions are based on calculations reported in the respective source studies rather than independent verification using a common dataset.

The financial implications of transportation optimization are further illustrated by the results for PT Tirta Utama Abadi. As presented in Table 2, the application of VAM and MODI reduced the company's distribution expenditure from IDR 21,794,083 to IDR 19,331,108 in November 2025, representing savings of 11.30%. A larger reduction of 15.20% was recorded in December 2025, when distribution costs decreased from IDR 20,803,010 to IDR 17,640,728. These results are consistent with Widia and Nuratri (2026), who reported

that transportation models could improve the allocation of mineral water deliveries between warehouses and distribution areas. The variation in savings between the two periods suggests that the financial benefits of optimization depend on prevailing distribution requirements, route costs, and available supply capacities. For businesses operating with limited margins, reductions in distribution expenditure may provide additional financial flexibility without requiring an immediate expansion of production facilities. The savings observed in this case, however, should be interpreted within the company's operational context rather than generalized as an expected efficiency rate for all distribution networks.

The findings also indicate that minimizing transportation costs does not necessarily address every component of logistics expenditure. In the J&T Express case, Sembiring et al. (2022) reported that the assignment method produced an optimal driver wage cost of IDR 713,499, whereas the driver costs associated with transportation allocations obtained through NWC and VAM amounted to IDR 1,185,333. This difference demonstrates that shipment allocation and personnel assignment represent related but distinct optimization problems. A distribution plan that minimizes shipment costs may not simultaneously minimize labor expenditure unless both decisions are incorporated into the mathematical model. Another operational consideration emerged from the medical device distribution case, where projected demand of 24,719 boxes exceeded the available supply of 23,125 boxes. The introduction of a dummy source representing 1,594 boxes allowed the transportation problem to be balanced mathematically. The study by Syaputri and Isya (2025) likewise highlighted the application of VAM and MODI to projected medical device distribution requirements. Such findings emphasize that dummy allocations are mathematical adjustments rather than physical shipments, and any remaining supply shortages must still be addressed through operational decisions. Transportation optimization therefore provides a useful analytical basis for distribution planning, but its practical application requires an understanding of the constraints excluded from the model.

The comparative results have implications for both transportation optimization theory and supply chain management practices. From a methodological perspective, the findings highlight the importance of distinguishing between the quality of an initial solution and the optimality of the final allocation. VAM's penalty-based procedure can generate efficient starting solutions, but its relative advantage depends on the characteristics of the transportation problem. The findings therefore support the complementary roles of initial allocation algorithms and optimality assessment rather than establishing the universal

superiority of a single method. From a managerial perspective, the results encourage companies to replace routine or intuition-based distribution decisions with systematic evaluations of transportation costs, warehouse capacities, and destination requirements. Operations managers may begin by constructing a transportation matrix, comparing feasible allocations, and verifying whether further cost reductions are possible through MODI or Stepping Stone. The relative cost differences illustrated in Figure 1 also demonstrate the importance of assessing method performance within comparable operational conditions, particularly when companies differ considerably in their distribution scale.

The practical value of this approach is especially relevant to small and medium-sized enterprises that face resource limitations and fluctuations in operating costs. An initial allocation method that produces a lower transportation cost can help managers identify more economical shipment patterns without changing the total quantity distributed. The combination of VAM and subsequent optimality testing may therefore serve as a practical decision-support framework for enterprises with multiple supply points and delivery destinations. The findings also suggest opportunities for integrating transportation optimization with other operational decisions, including vehicle scheduling, driver assignment, and inventory management. Such integration could improve the applicability of mathematical optimization in distribution systems where financial efficiency must be balanced against delivery reliability and service requirements. The contribution of the present study lies in bringing together findings from different business contexts to clarify the conditions under which transportation methods produce comparable or different cost outcomes.

Several limitations should be considered when interpreting the findings. The analysis relied on transportation costs and optimization outcomes reported in previously published case studies, rather than applying all methods to a newly collected, standardized dataset. Differences in company size, product characteristics, transportation networks, cost structures, and observation periods limit direct comparisons across cases. Some studies also reported incomplete information about alternative allocation methods, restricting the scope of comparison. The available evidence was insufficient to establish statistical differences in method performance or determine whether the reported cost reductions would remain consistent under changing operational conditions. The transportation models primarily considered direct shipment costs and simplified supply-demand relationships, without fully incorporating delivery time windows, vehicle capacity differences, fixed warehouse expenses,

or uncertain demand. A separate sensitivity analysis was also not available to establish how changes in unit transportation costs would affect the selected allocation patterns. Future research should apply competing optimization methods to comparable primary datasets, verify solutions using computational tools, and incorporate sensitivity analysis and additional operational constraints. These extensions would provide a stronger basis for evaluating the reliability and practical effectiveness of transportation optimization models under changing supply chain conditions.

CONCLUSION

The application of linear programming transportation models effectively minimizes distribution costs by aligning supply capacities with destination demands through the most cost-efficient routes. The synthesis of multiple empirical analyses reveals that Vogel's Approximation Method (VAM) consistently generates highly efficient initial solutions by systematically evaluating penalty costs across the entire distribution matrix. When these initial baselines are coupled with optimization tests such as the Stepping Stone and Modified Distribution (MODI) methods, the VAM solutions are frequently confirmed as the definitive global minimum cost. Conversely, methods that prioritize only local minimums, such as the Least Cost method, can result in higher total operational costs due to a lack of structural oversight in subsequent routing allocations.

This synthesis advances the practical application of operations research by demonstrating that mathematical optimization can systematically replace conventional, intuition-based logistical planning. The findings confirm the theoretical reliability of VAM and MODI as a combined analytical framework, proving their efficacy in generating measurable financial savings across diverse sectors, including manufacturing, medical device distribution, and logistics services. By grounding theoretical models in empirical enterprise data, this analysis bridges the gap between academic linear programming and practical supply chain management, offering a scalable strategy for small and medium enterprises seeking to maximize profit margins amidst rising operational and fuel expenses.

To build upon these foundational efficiency gains, future research must integrate more complex, real-world operational constraints into the transportation models. Researchers are encouraged to expand the analytical parameters to account for delivery time windows, distinct vehicle capacities, varying geographic topographies, and fixed warehouse

maintenance costs. Furthermore, future studies should apply comparative analytical approaches across a wider array of industries utilizing direct primary data, ensuring that the theoretical distribution frameworks remain robust, accurate, and adaptable to highly dynamic, multi-variable logistical environments.

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