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# *LINEAR PROGRAMMING FOR ALLOCATING TRANSPORTATION CAPACITIES IN FREIGHT PLANNING*

*Effective allocation of transport capacities is vital for motor transport enterprises engaged in freight transportation. As the demand for goods transportation rises, optimizing resource utilization becomes essential for ensuring timely deliveries, minimizing costs, and enhancing overall operational efficiency. Linear programming, a powerful tool in mathematical optimization, plays a key role in facilitating the rational distribution of limited resources. By framing the allocation problem as a linear program, enterprises can systematically identify the optimal use of their transport capacities, taking into account critical factors such as vehicle availability, delivery schedules, and associated costs. In the realm of operational planning, linear programming offers a structured and* *analytical approach to addressing the complexities inherent in freight transportation. This study delves into both the theoretical underpinnings and the practical applications of linear programming, showcasing its potential to significantly improve resource allocation strategies, boost efficiency, and reduce operational costs. Through the analysis of real-world examples and empirical data, the study provides valuable insights that can aid practitioners and researchers alike in refining logistics optimization practices, ultimately contributing to more efficient and cost-effective freight transport operations.*

*Keywords: linear programming, transportation capacities, operational planning, freight transportation, resource optimization.*

**Introduction**

Efficient allocation of transportation capacity is critical for road transport companies involved in freight logistics. As global trade and domestic logistics networks expand, the demand for timely and efficient transportation services is increasing. This requires strategic use of resources to meet delivery schedules, minimize costs and improve operational efficiency. Increased fuel consumption and vehicle emissions such as carbon monoxide and particulate matter not only contribute to pollution but also increase the cost of transportation.

State departments of transportation issue permits for oversized vehicles and manage restrictions such as varying road widths, inappropriate curves, weight restricted bridges, and low underpasses. Paper [1, p. 333] introduces a method to identify maximum-capacity paths with length constraints, using a linear-integer programming model and an arc-elimination procedure. This method optimizes routes with weight, width, and height restrictions, demonstrated to be efficient in route selection within the Tennessee highway network.

Study [2, p. 301] addresses challenges in truck-sharing, focusing on how it can expand transport capacity, reduce carbon emissions, and alleviate congestion. An exploratory qualitative approach reveals technical issues and external constraints, such as driving restrictions and seaport operating hours, but also emphasizes the importance of trust and coordination among carriers. The study suggests increasing hinterland transport capacity by utilizing idle truck slots and effectively managing truck-sharing challenges.

Article [3, p. 194] proposes a method to find maximal-capacity paths with length constraints, transforming networks to exclude excessively long routes. This method uses a modified depth-first search algorithm to improve route optimization.

Paper [4, p. 04023135] presents a multimodal transportation-as-a-service (MMTaaS) framework for personalized travel planning. The framework includes multimodal path planning, traveler-specific itineraries, and personalized recommendations, validated through a case study in Jiaxing City, China.

Article [5, p. 10576] explores advancements in enterprise information management with big data, proposing a short-term prediction model for bus passenger flow using a combined Stacked Denoising Autoencoder (SDAE) and bidirectional Long-Short Term Memory network (Bi-LSTM), showing improved accuracy in predictions.

Study [6, p. 78] investigates upstream supply chain issues in the logging industry, combining a literature review with case studies in Mississippi to develop a framework categorizing logistical challenges.

Efficient last-km delivery management is addressed in study [7, p. 124559], which introduces a Decision Support System (DSS) for optimizing driver sectors and routes using a Preference-Inspired Co-Evolutionary Algorithm with Goal vectors using Mating Restriction (PICEA-g-mr).

Finally, the study [8] solves the vehicle routing problem with limited capacity by using a hybrid whale optimization algorithm (hGWOA), which demonstrates superior performance in optimizing delivery distances using real-world examples in Vietnam. One of the most effective methods to solve this problem is linear programming (LP).

Linear Programming (LP) is a mathematical optimization technique used in all industries, including transportation, to aid in decision making by maximizing or minimizing a linear function under linear constraints. In transportation, LP optimizes the allocation of resources - vehicles, drivers, and fuel - resulting in cost savings, improved service, and more efficient use of resources [9].

QazAvtoJol, a trucking company in Kazakhstan, is an example of the application of LP in transportation logistics. The company faced challenges in optimizing its freight transportation capacity, including scheduling, resource allocation and cost management. This study shows how LP can solve these problems with an adapted model that other transportation companies can use [10, p. 124194].

The LP model considers key resources such as number of trucks, routes, and delivery times, with constraints related to vehicle capacity and driver availability. The goal of the model is to minimize operating costs while meeting these constraints. Implementation involves data collection, model formulation, and analysis of the results using tools such as LINGO to allow for optimal resource allocation and informed decision making. The study highlights the effectiveness of linear programming in optimizing transportation capacity, as evidenced by QazAvtoJol's efficiency gains and cost reductions. As demand for freight transportation increases, LP will be critical to maintain competitiveness and operational excellence. This study shows how LP can improve operational efficiency in real-world scenarios, providing a useful framework for similar businesses.

**Materials and methods**

This study used LINGO software, a comprehensive optimization tool designed to develop and solve a variety of optimization models, including linear, nonlinear (convex and nonconvex/global), quadratic, quadratically constrained, second-order cone, semidefinite, stochastic, and integer optimization models. LINGO combines a powerful modeling language with a robust environment for constructing and editing problems, as well as a set of efficient built-in solvers. The latest version, LINGO 21, contains significant improvements and new features.

JSC NC KazAutoJol, a company from Kazakhstan, provided practical transportation-related issues that served as the basis for the application of LINGO in this study. The company faced serious challenges in optimizing its transportation logistics, making it a relevant example of applying LINGO capabilities.

LINGO greatly accelerates development by allowing linear, nonlinear, and integer problems to be quickly formulated in a clear, easy-to-read format. Its modeling language supports intuitive expressions using sums and substring variables similar to traditional methods, making it easy to build and maintain models. LINGO utilizes multiple processor cores for faster model building and integrates seamlessly with databases and spreadsheets for efficient data management and reporting. LINGO has many fast built-in solvers that are automatically selected based on the model. Users can interactively build and solve models in the comprehensive LINGO environment with support for integration through DLL and OLE interfaces, and call it from Excel or database applications.

Detailed documentation and support tools, including a user manual and «Optimization Modeling with LINGO», facilitate quick learning of the program.

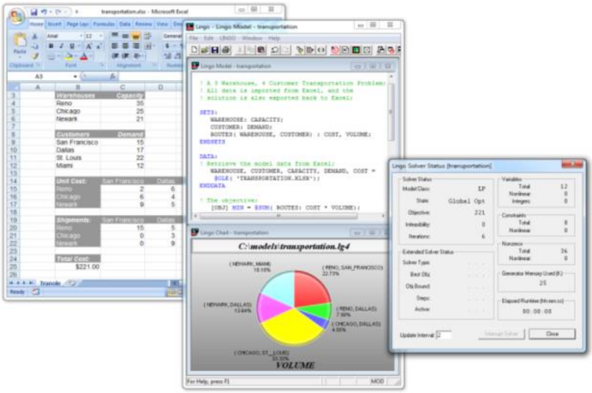

Figure 1 – LINGO software

**Results and discussion**

This example will illustrate the application of integer linear programming (ILP) to routing problems.

QazAvtoJol provides a specialized delivery service, connecting a starting point to six other cities in a four-state region. Upon receiving a request for service, QazAvtoJol dispatches a truck from the starting point to the city that requests service at the earliest opportunity (Figure 2).

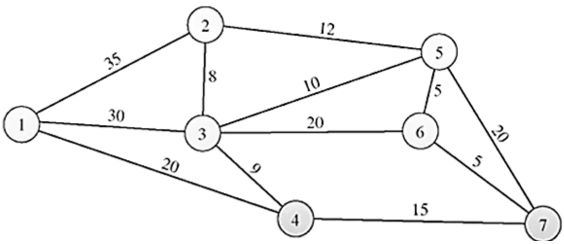


Figure 2 – Delivery service road map

When optimizing logistics for QazAvtoJol company, the main objective is to provide fast service while minimizing transportation costs. To achieve this goal, it is necessary to find the shortest route from the starting point (node 1) to the required destination (node 6) in a road network represented as a graph. The distances between the nodes are known, and the problem is to find the optimal path that minimizes the total distance.

This problem, although complex due to the scale of the graph, is essentially a shortest path problem. It can be solved using algorithms like Dijkstra or A*, which are designed for such scenarios. This problem is a decision making problem under certainty, since all distances are precisely known.

Initially, two potential paths are considered: the first path runs from node 1 to node 3, then from node 3 to node 6. The second path runs from node 1 to node 2, then from node 2 to node 3, and finally from node 3 to node 6. The first path includes segments (1, 3) and (3, 6) and the second path includes segments (1, 2), (2, 3) and (3, 6), adding an additional segment.

To formulate this problem in the framework of linear programming, we define binary decision variables xij, where xij is 1 if segment (i, j) is part of the optimal path, and 0 otherwise. The problem is to minimize the total distance, which involves computing and comparing the total distances of all potential paths.

By evaluating these paths and using optimization techniques, the most efficient route from node 1 to node 6 can be determined, which will effectively minimize the travel distance.

Table 1 – Decision variables

| № | Xij = 1 if the path starting at node I and ending at node j is selected; = 0 if not selected; | | |
|---|---|---|---|
| 1 | @BIN (X12); | @BIN (X34); | @BIN (X56); |
| 2 | @BIN (X13); | @BIN (X35); | @BIN (X57); |
| 3 | @BIN (X14); | @BIN (X36); | @BIN (X74); |
| 4 | @BIN (X23); | @BIN (X43); | @BIN (X75); |
| 5 | @BIN (X25); | @BIN (X47); | @BIN (X76); |
| 6 | @BIN (X32); | @BIN (X53); | @BIN (X52); |

To solve the path optimization problem, it is necessary to consider all the line segments present in the graph. Each potential path through the network includes a combination of these segments. In this context, each line segment is assigned a binary decision variable indicating its inclusion or exclusion from a given path.

Specifically, if the path passes through a particular line segment, the corresponding decision variable is assigned a value of 1. Conversely, if the path does not include that line segment, the variable is assigned a value of 0. This binary assignment effectively reflects whether each line segment is part of the optimal path.

Given the complexity of a network with many line segments, this approach requires considering all possible segments. For example, let us denote the line segment between nodes (1, 2) as X12. If the path being evaluated passes through this segment, X12 will be assigned the value 1. If the path does not pass through this segment, X12 will be assigned the value 0 (Fig. 3).

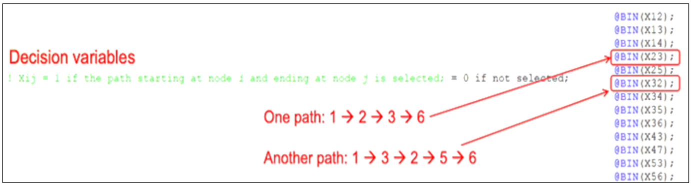


Figure 3 – Decision variables in LINGO software

In transportation route optimization, the decision variables Xij are classified as binary variables, i.e., they can only take the values 1 or 0. This binary character is crucial because it simplifies the problem formulation within the linear programming framework. Each variable Xij indicates whether a line segment (i, j) is included in the route (1) or not (0). By systematically applying these binary variables to all line segments, the problem of finding the shortest route to minimize the travel distance can be efficiently modeled and solved.

When using LINGO to define these decision variables, the @BIN function must be used and each line of code must end with a semicolon. This syntax ensures that the variables are correctly recognized as binary, which is very important to accurately model the inclusion or exclusion of line segments during the optimization process

In addition, it is important to consider line segments such as (2, 3) and (3, 2) as separate entities because of their directional nature. For example, one route may run from node 1 to node 2, then to node 3 and finally to node 6, while another route may run from node 1 to node 3, then to node 2, and then to node 5 before reaching node 6. In order to accurately model the routes, the directionality of these segments must be taken into account.

Moreover, line segments that terminate at node 1 should be excluded from consideration. Since node 1 is the starting point, any segment ending here would mean returning to the starting point, which is inefficient. Similarly, segments starting at node 6 should be excluded, since node 6 is the final destination, and including such segments would mean an unnecessary departure from the end point.

Following these guidelines – correctly defining the binary variables, respecting the directionality of the segments, and excluding inefficient paths - allows the problem to be modeled accurately. This approach ensures that the most efficient path minimizing the total travel distance is determined while respecting the constraints of the problem (Figure 4).

```
MIN= 35*X12 + 30*X13 + 20*X14 + 8*X23 + 12*X25 + 8*X32 + 9*X34 +
10*X35 + 20*X36 + 9*X43 + 15*X47 + 10*X53 + 5*X56 + 20*X57 +
15*X74 + 20*X75 + 5*X76 + 12*X52;
```

Figure 4 – Traveled total distance

The main objective of this optimization problem is to minimize the total distance traveled. Each line segment in the network has a known distance associated with it. For example, the distance from the starting point (node 1) to node 2 is 35 km. If we include the line segment (1, 2) in the optimal path, the corresponding decision variable X12 will be set to 1. This inclusion will add 35 km to the total travel distance, which is 35×X12 to the total distance.

Similarly, if the segment (2, 3) is part of the path, it contributes an additional distance of 8 km to the total travel distance. Thus, the term 8×X23 represents this contribution. To compute the total distance traveled, we sum the contributions from all included line segments, each weighted by its respective distance. This summation of products distance ij×Xij across all line segments gives the total travel distance.

The optimization problem is then formulated as minimizing this sum of distances. In LINGO, this is achieved using the MIN function to specify that the goal is to minimize the total distance.

Next, we need to consider the constraints that will ensure the validity of the solution. These constraints will be essential for ensuring that the path is feasible and adheres to the problem's requirements (Table 2).

Table 2 – Shortest Path

| № | Constraints |
|---|---|
| 1 | X12+X13+X14=1 |
| 2 | X23+X25=X12+X32+X52 |
| 3 | X32+X34+X35+X36=X13+X23+X43+X53 |
| 4 | X43+X47=X14+X34+X74 |
| 5 | X52+X53+X56+X57=X25+X35+X75 |
| 6 | X36+X56+X76=1 |
| 7 | X74+X75+X76=X47+X57 |

At Node 1, which represents Initial point, it is imperative to ensure that the truck departs from this node. There are three possible outgoing line segments from Initial point: (1, 2), (1, 3), and (1, 4). To formalize this requirement, we need to guarantee that at least one of these segments is used. This can be enforced using a conditional constraint that stipulates the sum of the decision variables X12, X13, and X14 must equal 1.

Similarly, for Node 2, the path's interaction with this node must be considered. If the path includes Node 2, it must both arrive at and depart from this node. The arrival at Node 2 can occur via segments (1, 2), (3, 2), or (5, 2). The departure from Node 2 can be via segments (2, 3) or (2, 5). To enforce this, we establish two constraints:

If the truck departs from Node 2, represented by X23+X25=1, then it must have arrived at Node 2, ensuring that X12+X32+X52=1;

Conversely, if the truck does not pass through Node 2, X23+X25=0, then no arrivals should occur at Node 2, requiring X12+X32+X52=0.

Applying this logic to all nodes in the network will result in a total of 7 constraints, each ensuring the correct flow of the path through each node. These constraints ensure that the inclusion or exclusion of each node is properly accounted for in the optimization model.

The complete LINGO model including these constraints and the objective function for minimizing the total trip distance is presented for further study (Figure 5 a).

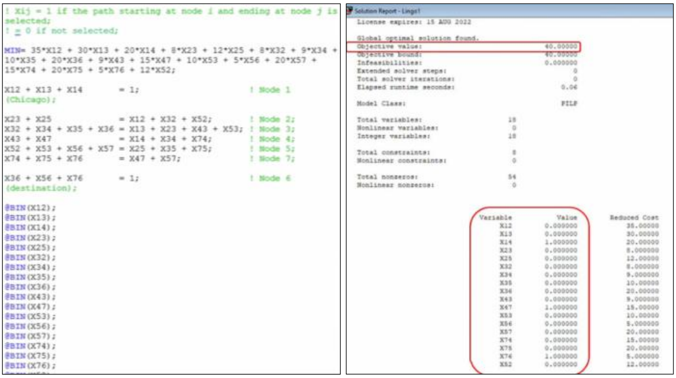


Figure 5 – Data: a – input model to LINGO, b – optimal strategy

The optimal routing solution (Fig. 5 b) for a freight company involves traveling from a starting point (node 1) to node 4, then to node 7 and finally to node 6. This particular path was determined to be the shortest among all possible alternatives with a total distance of 40 km.

It is important to note that the graph used in this analysis was not drawn to scale, making it much more difficult to visually determine the shortest path. Due to the lack of proportional representation of distances on the graph, determining the shortest path by visual inspection alone would be very difficult and unreliable.

In practice, the determination of the best path is not achieved by visual inspection but by algorithmic methods. Such methods provide an accurate computation of the shortest path by systematically evaluating all possible routes based on their respective distances, which ultimately leads to the determination of the route with the minimum total distance.

**Conclusions**

Advanced optimization algorithms and methods, such as the hybrid whale optimization algorithm and decision support system (DSS), are presented for solving last kilometer delivery and vehicle routing problems. The case study of QazAvtoJol demonstrates the practical utility of linear programming for optimizing resource allocation and cost management. The study highlights the value of advanced optimization tools and strategies to meet the changing needs of the transportation industry, offering frameworks and methodologies to improve operational efficiency, cost reduction, and environmental sustainability. Future research can explore innovative optimization techniques, expand truck-sharing practices, and improve multimodal systems to address emerging transportation challenges.

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# ЖҮК ТАСЫМАЛЫН ЖОСПАРЛАУ КЕЗІНДЕ КӨЛІК ҚУАТЫН БӨЛУГЕ АРНАЛҒАН СЫЗЫҚТЫҚ БАҒДАРЛАМАЛАУ

*Көлік қуатын тиімді бөлу жүк тасымалдаумен айналысатын автокөлік кәсіпорындары үшін өте маңызды. Жүк тасымалына сұраныс артқан сайын ресурстарды пайдалануды оңтайландыру уақтылы жеткізуді қамтамасыз ету, шығындарды азайту және жұмыстың жалпы тиімділігін арттыру үшін қажет болады. Сызықтық бағдарламалау, қуатты математикалық оңтайландыру құралы, шектеулі ресурстарды ұтымды бөлуде шешуші рөл атқарады. Бөлу мәселесін сызықтық бағдарлама ретінде тұжырымдай отырып, кәсіпорындар көлік құралдарының болуы, жеткізу кестелері және байланысты шығындар сияқты маңызды факторларды ескере отырып, өздерінің көлік қуаттарын оңтайлы пайдалануды жүйелі түрде анықтай алады. Операциялық жоспарлау саласында сызықтық бағдарламалау жүк тасымалына тән күрделі мәселелерді шешуге құрылымдық және аналитикалық тәсілді ұсынады. Бұл зерттеу ресурстарды бөлу стратегияларын айтарлықтай жақсарту, тиімділікті арттыру және операциялық шығындарды азайту үшін оның әлеуетін көрсететін сызықтық бағдарламалаудың теориялық негіздерін де, практикалық қосымшаларын да қарастырады. Нақты мысалдар мен эмпирикалық деректерді талдау арқылы зерттеу тәжірибешілерге де, зерттеушілерге де логистиканы оңтайландыру әдістерін жетілдіруге көмектесетін құнды түсініктер береді, бұл сайып келгенде жүк тасымалының тиімділігі мен табыстылығын арттыруға ықпал етеді.*

*Кілтті сөздер: сызықтық бағдарламалау, тасымалдау мүмкіндіктері, жедел жоспарлау, жүк тасымалдау, ресурстарды оңтайландыру.*

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## ЛИНЕЙНОЕ ПРОГРАММИРОВАНИЕ ДЛЯ РАСПРЕДЕЛЕНИЯ ТРАНСПОРТНЫХ МОЩНОСТЕЙ ПРИ ПЛАНИРОВАНИИ ГРУЗОПЕРЕВОЗОК

*Эффективное распределение транспортных мощностей жизненно важно для автотранспортных предприятий, занимающихся грузоперевозками. По мере роста спроса на грузоперевозки оптимизация использования ресурсов становится необходимой для обеспечения своевременных поставок, минимизации затрат и повышения общей эффективности работы. Линейное программирование, мощный инструмент математической оптимизации, играет ключевую роль в рациональном распределении ограниченных ресурсов. Сформулировав проблему распределения в виде линейной программы, предприятия могут систематически определять оптимальное использование своих транспортных мощностей, принимая во внимание такие важные факторы, как наличие транспортных средств, графики поставок и сопутствующие расходы. В сфере оперативного планирования линейное программирование предлагает структурированный и аналитический подход к решению сложных задач, присущих грузовым перевозкам. В данном исследовании рассматриваются как теоретические основы, так и практические приложения линейного программирования, демонстрирующие его потенциал для значительного улучшения стратегий распределения ресурсов,* *повышения эффективности и снижения операционных затрат. Благодаря анализу реальных примеров и эмпирических данных в исследовании приводятся ценные сведения, которые могут помочь как практикам, так и исследователям в совершенствовании методов оптимизации логистики, что в конечном итоге будет способствовать повышению эффективности и рентабельности грузовых перевозок.*

*Ключевые слова: линейное программирование, провозные возможности, оперативное планирование, грузовые перевозки, оптимизация ресурсов.*

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