Optimization of Material Transport Routes in Road Construction Projects through Linear Programming

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Abstract
The present study develops a linear programming model for optimizing material transport routes in road construction projects. Taking into account factors such as load capacity, distance, travel time, transportation costs, and environmental restrictions, the aim is to find the optimal solution that minimizes total costs and ensures the timely and sustainable delivery of materials. The research conducts a case study of the Combapata Road in Cusco Peru as an application of the proposed model, from which project data such as unit costs, volume, distances, times, and transport unit speeds were inputted into the developed algorithm. The results reveal a minimum total cost of USD 67,226.58 per m3, representing an 11.6% reduction compared to the original project cost calculated using traditional methods. This approach demonstrates the effectiveness and potential of linear programming in optimizing infrastructure projects, offering tangible benefits in terms of efficiency and costs.

Keywords
Optimization, Transportation, Linear Programming, Road Construction.

1. Introduction

The growing urban development and infrastructure in the contemporary world demand efficient and sustainable management of road construction projects. Among the various challenges of these projects, the logistics of material transportation plays a critical role in terms of costs, construction times, and environmental sustainability (Muerza & Guerlain, 2021; Naz et al., 2022). With the heterogeneity of necessary materials and complex logistical constraints, optimizing transportation routes can have a significant impact on the overall efficiency of road construction projects (Alanazi et al., 2022; Choudhari & Tindwani, 2017).

Regarding route optimization, the Traveling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP) are the most studied models (Toth & Vigo, 2014). These problems, which focus on minimizing the total distance or time of travel, have been adapted to consider specific constraints of road construction, such as load capacity and delivery time (Yang & H. Bell, 1998).

Linear programming, a widely used mathematical method in operations research for solving optimization problems, provides the theoretical and practical framework to address this challenge (Dordevic et al., 2022; Zhao et al., 2021; Zhou et al., 2022). Through the formulation and solving of a linear programming model, decision-makers are provided with a useful tool for the efficient planning and management of material transportation in road construction. Additionally, a hybrid algorithm has been developed, combining an interior point method and column generation for large linear programs arising in discrete optimal transportation problems, demonstrating its effectiveness in terms of computation time and memory usage (Zanetti & Gondzio, 2023). (Yi et al., 2020) It focused on planning the transportation of prefabricated products, achieving cost savings through a mathematical programming model. Finally, the consistent vehicle routing problem has been addressed through formulations based on set partitioning, providing insights into the adoption of consistency measures in practice (Wang et al., 2022).

The current issue lies in the deficiencies of current processes for route selection, cost evaluation, and time and distance assessment in road construction projects in the application of optimization techniques and models. This leads to counterproductive effects by not adequately considering load capacity, delivery schedules, and resource management assigned to the project. Consequently, decision-making focused on optimizing processes, reducing operational costs, and efficiently managing available resources becomes challenging. It is necessary to incorporate more robust analytical tools to improve the planning of material transportation and distribution in these types of projects.

2. Methodology

Establishing a rigorous research methodology is indispensable in engineering to ensure the validity of findings and the achievement of the objectives set forth in the study (Paniura et al., 2023). Therefore, initially, a literature review of previous studies on transportation route optimization and applications of linear programming in road construction projects was conducted. This allowed for the identification of relevant variables for the model and methodological considerations to be taken into account. Subsequently, a linear programming model was formulated defined by an objective function that minimizes transportation costs, subject to constraints associated with vehicle load capacity, delivery schedules, time windows, environmental limitations, and budgetary constraints.

The model was solved using specialized software in linear programming to find optimal routes between quarries, depots, and work fronts. The results were validated by comparing them with real data from the case study. Finally, a quantitative analysis of the input data was conducted, including routes, locations, transportation capacity, costs, schedules, operational, and budgetary constraints. This allowed for the evaluation of the effectiveness of the model in increasing productivity and efficiency in transportation resource management in road projects.

3. Proposed quarry transportation solution

3. 1 Definition of variables

X_{ij}: It is the volume (m3) of material that will be transported from quarry i to work front j on the road that starts at mileage 0+000 to km m+000, with a length of "m" kilometers.

i = 1, …, n {1=B-1, …, n=B-n}

j=1, …, m {1=km 0+000 al km 1+000, …, m= km m-1+000 al km m+000}

The objective function aims to minimize the total transportation cost. Assuming that the transportation cost per cubic meter per kilometer is constant and denoted as c. The objective function may be complicated to define without knowing the specific transportation costs. However, if we assume a unit transportation cost for simplification, the objective function will simply focus on minimizing the total distance traveled by the material, which is not typically how these problems would be modeled, but we will focus on resource allocation:

$$Minimize \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} * x_{ij}$$

Where C_{ij} is the distance from quarry i to work front j of the road. Capacity constraints are associated with the maximum volumes of each material.

$$\sum_{j=1}^{m=25} x_{1j} \leq 5200$$

$$\sum_{j=1}^{m=25} x_{2j} \leq 8100$$

$$\sum_{j=1}^{m=25} x_{3j} \leq 10200$$

The demand constraints at each kilometer of the road correspond to:

$$\sum_{i=1}^{n=3} x_{ij} \leq \text{ variable (according to Volume from Table 2)}$$

∀j=1, 2, …, 25. Likewise, there is a non-negativity constraint. ∀j=1, 2, …, 25

$$x_{ij} \geq 0 \text{ (according to Volume from Table 3)}$$

4. Case Study

The study will be conducted by analyzing the optimization of transportation routes in the construction of the Combapata Road, which is a public investment project for the improvement of a local road in Cusco, Peru. The road is in the district of Combapata, province of Canchis, in the region of Cusco, Peru. It is situated at an altitude of 3,481 meters above sea level and has a temperate climate.

4. 1 Transportation of granular material from quarries

The first linear programming problem arises in the transportation of materials from quarries for filling in road construction. For the construction of the pavement, it is required that a layer of filling material be placed beneath it, with the material being aggregate from a quarry in the area, as shown in Figure 1.

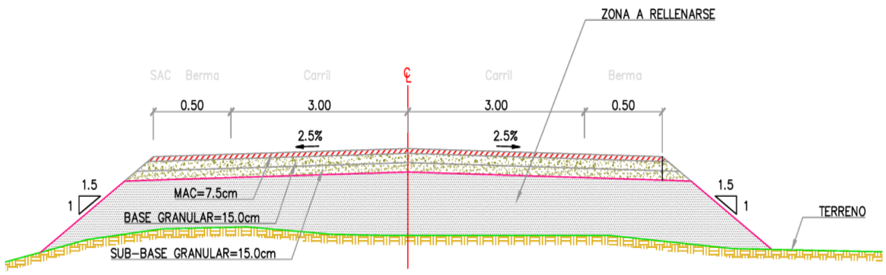

Fig. 1. Cross-section in fill for a road.

In urban road projects, it is common to use products from an aggregate supply company; however, in highway construction, the surrounding environment often offers aggregate quarries that, after conducting the respective soil studies, can be used as sources of material supply. The road under study has a length of 25.889 km and includes the Quarries indicated in Table 1.

Table 1. Table of data on quarry locations and volumes

Quarry	Location (mileage)	Access (km)	Volume (m3)
B-1	2+920	0.005	5,200
B-2	15+100	0.025	8,100
B-3	25+889	1.080	10,200
Total Volume			23,500

Below is Table 2, which identifies how the Project Manager in charge of preparing the technical file has assigned the different sections to be executed to different quarries.

Table 2. Assignment of work fronts to project quarries.

Start	End	Volume (m3)	Assigned quarry	Start	End	Volume (m3)	Assigned quarry
0+0.00	1+000.00	963.18	B-1	13+000.00	14+000.00	195.04	B-2
1+000.00	2+000.00	730.79	B-1	14+000.00	15+000.00	191.21	B-2
2+000.00	3+000.00	973.86	B-1	15+000.00	16+000.00	754.73	B-2
3+000.00	4+000.00	364.57	B-1	16+000.00	17+000.00	676.05	B-3
4+000.00	5+000.00	666.34	B-2	17+000.00	18+000.00	682.27	B-3
5+000.00	6+000.00	132.72	B-2	18+000.00	19+000.00	433.95	B-3
6+000.00	7+000.00	792.44	B-2	19+000.00	20+000.00	303.28	B-3
7+000.00	8+000.00	963.14	B-2	20+000.00	21+000.00	835.57	B-3
8+000.00	9+000.00	968.82	B-2	21+000.00	22+000.00	475.59	B-3
9+000.00	10+000.00	466.43	B-2	22+000.00	23+000.00	611.56	B-3
10+000.00	11+000.00	967.84	B-2	23+000.00	24+000.00	687.28	B-3

11+000.00	12+000.00	842.51	B-2	24+000.00	25+000.00	225.05	B-3
12+000.00	13+000.00	677.14	B-2	25+000.00	26+000.00	787.67	B-3
		Total Volume			16,369.03		

Prior to initiating the linear programming model, the costing of transports was conducted under the initial conditions of the project. Subsequently, with the developed linear programming model, we will carry out a redistribution of transports to verify if such distribution is optimal. Then, we will propose to the linear programming model to be dynamic regarding capacity. Table 4 shows the distribution of transportation and its costing under the original conditions of the project.

Table 3. Calculation of distance and transportation costs

Start	End	Center of gravity	Volume (m3)	Quarry	Location	Access (km)	Transport distance (km)	Transport a) Dist <1 km	Transport b) Dist >1 km
		c			a	b	|a +b -c |	m3. km	m3. km
0+0.00	1+000.00	0+500.00	963.18	B-1	2+920.00	0.005	2.43	963.18	1,372.53
1+000.00	2+000.00	1+500.00	730.79	B-1	2+920.00	0.005	1.43	730.79	310.59
2+000.00	3+000.00	2+500.00	973.86	B-1	2+920.00	0.005	0.43	413.89	-
3+000.00	4+000.00	3+500.00	364.57	B-1	2+920.00	0.005	0.58	209.63	-
4+000.00	5+000.00	4+500.00	666.34	B-2	15+100.00	0.025	10.63	666.34	6,413.52
5+000.00	6+000.00	5+500.00	132.72	B-2	15+100.00	0.025	9.63	132.72	1,144.71
6+000.00	7+000.00	6+500.00	792.44	B-2	15+100.00	0.025	8.63	792.44	6,042.36
7+000.00	8+000.00	7+500.00	963.14	B-2	15+100.00	0.025	7.63	963.14	6,380.80
8+000.00	9+000.00	8+500.00	968.82	B-2	15+100.00	0.025	6.63	968.82	5,449.61
9+000.00	10+000.00	9+500.00	466.43	B-2	15+100.00	0.025	5.63	466.43	2,157.24
10+000.00	11+000.00	10+500.00	967.84	B-2	15+100.00	0.025	4.63	967.84	3,508.42
11+000.00	12+000.00	11+500.00	842.51	B-2	15+100.00	0.025	3.63	842.51	2,211.59
12+000.00	13+000.00	12+500.00	677.14	B-2	15+100.00	0.025	2.63	677.14	1,100.35
13+000.00	14+000.00	13+500.00	195.04	B-2	15+100.00	0.025	1.63	195.04	121.90
14+000.00	15+000.00	14+500.00	191.21	B-2	15+100.00	0.025	0.63	119.51	-
15+000.00	16+000.00	15+500.00	754.73	B-2	15+100.00	0.025	0.38	283.02	-
16+000.00	17+000.00	16+500.00	676.05	B-3	25+889.00	1.08	10.47	676.05	6,401.52
17+000.00	18+000.00	17+500.00	682.27	B-3	25+889.00	1.08	9.47	682.27	5,778.14
18+000.00	19+000.00	18+500.00	433.95	B-3	25+889.00	1.08	8.47	433.95	3,241.17
19+000.00	20+000.00	19+500.00	303.28	B-3	25+889.00	1.08	7.47	303.28	1,961.92
20+000.00	21+000.00	20+500.00	835.57	B-3	25+889.00	1.08	6.47	835.57	4,569.73
21+000.00	22+000.00	21+500.00	475.59	B-3	25+889.00	1.08	5.47	475.59	2,125.41
22+000.00	23+000.00	22+500.00	611.56	B-3	25+889.00	1.08	4.47	611.56	2,121.50
23+000.00	24+000.00	23+500.00	687.28	B-3	25+889.00	1.08	3.47	687.28	1,696.89
24+000.00	25+000.00	24+500.00	225.05	B-3	25+889.00	1.08	2.47	225.05	330.60
25+000.00	26+000.00	25+500.00	787.67	B-3	25+889.00	1.08	1.47	787.67	369.42
Volume			16,369.03			Quantity of traspotation		15,110.71	64,809.93
					Unit cost			USD 2.68	USD 0.55
					Partial cost			USD 40,555.50	USD 35,711.24
					Total cost				USD 76,266.74

5. Results and analysis

To carry out the analysis of minimum cost through linear programming, initially, the costs were calculated in relation to the distances from the quarries (origin i) to each of the kilometers requiring fill material (destination j). For this purpose, we used the data provided in Table 4, which are calculated according to the specificities of each project.

Table 4. Costs calculated through unit price analysis.

Quarries	Value	Unit
Dump truck	15	m3
Loading time	4.7	min
Unloading time	3	min
Outbound speed	20	km/h
return speed	25	km/h
Price per hour of loader	54.45	USD
Price per hour of dump truck	84.72	USD

Table 4 shows that the dump trucks cover the same distances at higher speeds when empty than when loaded with fill material. Additionally, loading times are 36.2% longer than unloading times, and the costs per hour for a round trip cycle are USD 139.17 . Using this information, the costs (C_{ij}) based on the distances covered by the transport units to each kilometer of the road were calculated, as shown in Table 5. This matrix will be used in the algorithm to determine the minimum total cost.

Table 5. Assignment of work fronts to the project quarries

Quarry	Km-0	Km-1	Km-2	Km-3	……	Km-25	Supply (m3)
B1	13.552	10.033	6.514	7.042	……	84.464	5200
B2	56.486	52.967	49.448	45.929	……	41.530	8100
B3	98.168	94.649	91.129	87.610	……	6.475	10200
Demand (m3)	963.18	730.79	973.86	364.57	……	787.67	

The cost obtained through optimization is USD 67,266.58 per m3 and represents a reduction of USD 9,038.84 per m3 compared to the traditionally calculated cost in Table 4; in percentages, the savings amount to 11.6%. Efficiency in road construction projects is achieved not only through the optimization of material transport routes, as demonstrated in the Combapata highway project in Cusco, Peru, where the application of linear scheduling models resulted in a significant cost reduction, but also through the implementation of adaptive and resilient risk management strategies. The latter are crucial in contexts affected by extreme weather events, as evidenced on the Oyon-Ambo highway during the 2019 El Niño event, where proactive risk management minimized the negative impact on infrastructure (Ariza Flores & Portocarrero, 2024; Ariza Flores & Salvador, 2024). These approaches highlight the importance of planning and adaptability in the construction of resilient road infrastructure.

6. Conclusions

The present methodology demonstrates a proposal of linear programming that can be utilized in optimizing transportation routes, controlling the load capacity of transport units, and supplying materials from nearby depots to the construction site. This allows for considering and organizing all variables involved in the process of minimizing transportation routes and goals. Within the case study, the proposal enabled the minimization of transportation costs by maximizing storage capacity and volume in transportation. Additionally, this model can be complemented with information from other operational areas in the road construction project and other requirements of the work to expand the model and generate a more significant cost minimization for the project. The limitations of this study lie in the adaptability and sensitivity of the linear programming model to different project sizes, geographical variations, and fluctuations in parameters such as costs and material availability. The effectiveness of the model can be affected by these factors, along with operational challenges and logistical constraints in its practical implementation. Recognizing these limitations is crucial for future research and the actual application of the model in the logistic optimization of road construction projects.

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