Optimal Location of Crashing Plants for Transportation of Base Course Material during the Construction Phase: A Case Study from a South American Project.

Ubicación Optima de Plantas de Chancado para el Transporte de Material de Base Granular durante la etapa de Construcción: Un caso de Estudio de un Proyecto en Sudamérica.

F. Araya[1,2], A. Vila[2]

[1]Departamento de Obras Civiles, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile.
[2]Construction Engineering and Project Management program, The University of Texas at Austin, USA.
felipe.araya@usm.cl. teléfono: +56 32 265 4185.

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Abstract

The transportation of base-course materials during construction is a challenging process of infrastructure projects, involving sub-processes such as quarrying, crushing, hauling, placement and compaction. The high cost of transporting base-course materials increases the total cost of the construction project. Thus, minimizing the cost of the transportation of base-course material during the construction may improve the performance in terms of highway infrastructure projects cost. This research presents an optimization model based on linear programming of the cost of transportation for base-course material that accounts for costs of extracting material, transportation from the quarry to the crushing plant, the cost of crushing material, transportation from the plant to the field, and the installation in the field. The proposed model is then implemented on a highway project constructed in Peru. The results emphasize the relevance of the location of the crushing plants within the project area and its impact on transportation costs. For instance, in the case study presented, the lowest cost was obtained when installing two crushing plants instead of one. The principal contribution of this study is providing an approach for construction managers and engineers providing better information to make decisions during the planning of base-course construction processes for highway infrastructure projects.

Resumen

El transporte de materiales base durante la etapa de construccion es un proceso con desafios para los proyectos de infraestructura que involucra procesos como la extraccion, chancado, transporte, colocacion y compactacion. El alto costo del transporte de materiales base aumenta el costo total de construir un proyecto. Por lo tanto, minimizando el costo de transporte de material base durante la construccion puede mejorar el desempeno en terminos de costo en proyectos de infraestructura. Por lo tanto, esta investigacion presenta un modelo de optimizacion basado en programacion lineal del costo de transportar material base que considera los costos de: extraccion del material, transporte desde la cantera de extraccion hasta la planta de chancado, el costo de chancado del material, transporte desde la planta hasta el terreno, y la instalacion en el terreno del Proyecto. El modelo propuesto es implementado en un Proyecto de carretera construido en Peru. Los resultados enfatizan la importancia de la ubicacion de la planta de chancado dentro del proyecto y los impactos en los costos de transportar el material. Por ejemplo, en el caso estudio presentado el costo mas bajo fue obtenido cuando se consideraron dos plantas de chancado en lugar de solo una. La contribucion principal del presente estudio es entregar un metodo para los administradores de proyectos de construccion e ingenieros que provee mayor informacion para la toma de decisiones durante la planificacion de los procesos constructivos de capas base en proyectos de infraestructura de carreteras.

1. Introduction

Highways projects are of high relevance for the development of countries. These projects improve the quality of life of citizens (e.g., providing connectivity and facilitating transportation among different regions within the country), and incentivize the economic growth of nations. Additionally, due to the urbanization trends from last decades—e.g., for first time in human history more population are residing in urban than in rural areas (Habitat U.N., 2016), so the demand for additional highway infrastructure is likely to increase in the upcoming years. However, one of the barriers that countries around the globe will face (more likely developing countries), are the financial limitations faced while responding these increased demands for infrastructure. Alternatives to reduce the costs of transportation infrastructure, namely highway projects, are required, thus reducing the cost associated to development of transportation infrastructure may facilitate the construction of this type of projects, which is fundamental from a developing nations standpoint.

One of the most expensive activities of highway construction projects is the allocation of earthwork (Bogenberg et al., 2015; de Lima et al., 2012; Dell'Amico et al., 2016; Karimi et al., 2007; Stark and Mayers, 1983), which involves finding the most economically convenient way to cut and fill sections of the project, and to estimate the volumes to be moved. Although the process of estimating the volume to be excavated is relatively simple, the execution of the excavation process is not (Peurifoy and Oberlender, 1991); an improper execution may lead to adverse effects such as delays or additional costs during the earthwork process. Thus, improving the understanding of earthwork activities becomes relevant for construction companies and engineers to minimize such potential negative impacts, specifically, regarding the financial performance of highway projects. The performance of the earthwork process is influenced mainly by two type of factors, the existing conditions of the project such as length of the project, soil conditions, and weather conditions in the project location; and management factors, for instance the equipment and methods used to perform the earthwork, which determine the cost of the earthwork process. Although it is essential to have a better understanding of all the variables that influence the earthwork process, this study is focused on the management of the transportation costs related to the project, namely modeling the cost of the transportation of base-course material during the construction of highway projects and the optimization of such cost.

In the existing literature, the first approach included the method of mass diagram Mayer and Stark (1981), which is a graphical representation of earth volumes to determine the sections to be cut and filled, and the quantities of material to be transported. However, this method suffered from multiple limitations, for instance, it was only applicable to linear roads, was not able to include mixed soils in the model, and was time-consuming and prone to error (Henderson et al., 2003). Consequently, multiple studies have been developed to overcome these limitations of the mass diagram, mainly implementing optimization techniques such as linear programming (Bogenber et al., 2015; de Lima et al., 2012; Liu and Lu, 2015; Yi and Lu, 2016), fuzzy linear programming (Karimy et al., 2007), or heuristic algorithms (Marzouk and Moselhi 2004; Nassar et al. 2011). Additionally, in recent years, the implementation of new technologies such as GIS and BIM have been explored to enhance different modeling aspects from the earthwork process in construction projects (Kim et al., 2015; Moselhi and Alshibani 2009; Tanoli et al., 2018).

Linear programming models have been extensively used to model earthworks during highway projects due to its effectiveness and simplicity. For example, de Lima and colleagues (2012) developed a model to optimize the excavation and paving processes, focused on the geometry and geotechnical characteristics of the project, and the allocation of materials to minimize the construction cost. Their results showed that the implemented model might provide valuable information for engineers and managers during the planning phase of the project regarding the optimal cost of construction. Similarly, Bogenberg et al. (2015) proposed a two-step optimization model for earthwork in highway construction. The first step involved minimizing the flow of construction materials during the entire duration of the project, according to the corresponding schedule. Then, the second step involved optimizing the distribution for each material involved in the construction process, notably not only excavation materials were taken into account, but also materials for recycling and filling were included. The model was implemented during the construction of a highway project in Europe, and the results showed a successful implementation of the model. Based on the claim that real-world projects present inherent uncertainty related to their execution, Karimy et al. (2007) suggested the inclusion of uncertainty to the existing model by modeling unit costs and borrow pits/disposal capacities as non-deterministic values, while minimizing the cost of the earth moving process. The results suggested that by including fuzzy variables to the model, engineers and managers might generate different models more representative of the real conditions. However, such additional information increase the computational cost of models (Karimy et al. 2007).

Regarding the implementation of heuristic algorithms to optimize earthwork in highway construction projects, techniques such as genetic algorithms are newer than linear programming. The main difference between these two techniques, linear programming finds the optimal solution according to the defined objective function and constraints, while in the case of genetic algorithms the solution found may not necessarily be optimal. Marzouk and Moselhi (2004) implemented a genetic algorithm to assess the trade-offs between time and costs of earthmoving operations. The results showed that this type of technique is well suited for what-if analysis for decision-makers, which can be useful when comparing multiple alternatives during the planning phase. Furthermore, there are studies in which the methodologies previously discussed have been combined (Lin et al., 201; Moselhi and Alshibani, 2009). For example, Moselhi and Alshibani (2009) combined genetic algorithms, linear programming, and GIS, while implementing a model to optimize the planning of earthmoving operations, as well as quantities of earth to be cut and filled and placed at different landfill sites according to project constraints. Finally, in recent years, the implementation of new technologies, such as GIS and BIM has also been transferred to the development of earthwork optimization models (Kim et al., 2015; Tanoli et al., 2018). For instance, Kim et al. (2015) developed a framework to integrate data from BIM with GIS platform for infrastructure projects. Then, that information was used to feed a genetic algorithm to optimize cut and fill operations. Consequently, generating an optimal construction plan (Kim et al., 2015).

As previously discussed, multiple studies in the literature have focused mostly on the optimization side of the problem; however, a significant limitation in the literature is the application of such approaches to real construction projects; specifically in regions other than North America and Europe. Considerable differences among these geographic regions such as skilled labor availability, contracting law, the technology available, and different culture and costs from the construction workers may have a considerable impact on earthwork operations. As such, this study contributes to the body of knowledge by implementing a linear programming based optimization model in the context of a real project developed in South America, which provides a practical framework to obtain information for the decision-making process of engineers and managers during the planning phase of highway construction projects. Furthermore, for the solution of the model, it was used Microsoft Excel, which is a familiar interface for engineers and construction managers. This interface facilitates the use of this optimization approach for professional that do not master programming skills. Another potential contribution of this study is for construction engineering teaching purposes. The study of a specific methodology in the context of a real construction project may provide a more intuitive approach for students learning about optimization techniques in construction engineering and management schools. Araujo L.S., Ramos H., Coelho S.T. (2006). Pressure control for leakage minimisation in water distribution systems management. Water Resources Management, 20: 133-149.

2. Methodology

In this section, the optimization model is described and explained, as well as the variables used to develop the model.

2.1 Construction Process components

The transportation of the construction materials to build the base course in highway projects may be conceptualized in different ways; nonetheless, in this study, we understand this process as represented in **Figure 1.** As such, the entire process encompasses the quarrying process (hauling raw material from quarries to crushing plant), the crushing process (hauling granular material from crushing plant to highway stages), and the installation of the granular material in the field.

This model represents the construction processes involved during a highway project and allows analyzing different conditions to calculate the costs involved transporting base course materials. For example, the model considers the travels that tracks must do in order to deliver aggregates from the quarrying site/plant to the construction site. The model optimizes the cost of the entire process subjected to different types of restrictions such as resources constraints, physical constraints, and geometric constraints that are explained below.

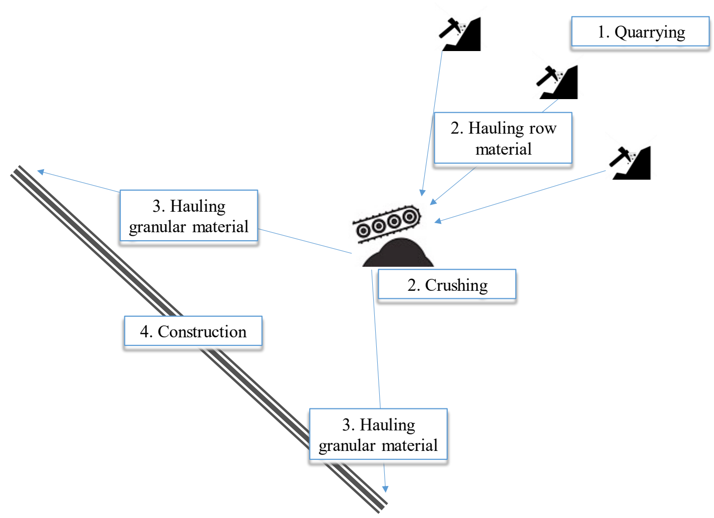

Figure 1 Base course construction phases (own elaboration).

2.2 Proposed Model

The model uses a function to represent the cost of transporting base course materials during a highway construction project; such cost considers the location of stone quarries, the location of crushing plants, and hauling distance conditions.

The objective function of the model will represent the total cost (sum of the cost of all five stages) of transport earthwork volumes along the base course construction process, from Quarrying location points to the crushing plant and then from the crushing plant to the construction site. The cost to move earth volume during each stage will be calculated such as a unit cost multiplied by the volume of earth that is being moved. The unit costs for each of the five stages are estimated based on the information available from the case study presented in the next sections—i.e., unit costs of their processes and cost of a crushing plant.

The constraints associated to the problem to be modeled have been identified as the following types: (1) physical limitations for the capacity of quarrying location points to provide material to the crushing plant to generate the final material to be moved. (2) The capacity of the crushing plant to process the original material and create the final material to be installed on the construction points. (3) The amount of earth volume demanded by each construction node will be considered constant and will depend on how many nodes are used to divide the problem. (4) The topology of the different paths that earth volume can take because the distance between points is considered as the minimum distance ("as the crow flies"). However, the model considers these limitations including a different unit cost when the earth volume is moved with or without slope, and when trucks that move the material to the construction site are going to leave the material (full condition) or going back to the plant (empty condition). The decision variables are defined as the earth volume to be moved between the quarrying location points and the crushing plant to generate the final material to be installed, and the earth volumes of material from the crushing plant to the construction site. Each type of travel will have different unit costs, depending on how far are they from the plant.

A limitation of this study is that the information to generate the unit costs between the different locations connecting the different paths along the process comes from a real project done in South America, which corresponds to the case study presented in this manuscript. It is important to emphasize this limitation because for infrastructure projects with a similar scope, but located in other countries; these values might differ. For instance, in South America labor costs are lower when compared with North America, limiting the direct transferability of results in different countries. Nonetheless, the methodology implemented during this study can be transferred to highway construction projects located in other regions.

2.3 Optimization Model

Figure 2 illustrates the abstraction of the problem being analyzed in this study. Furthermore, the formulation of the optimization model explained below is based on the processes shown in **Figure 2.** The model shows the sequence of activities required to build the base course of a highway project. The process starts with the quarrying process, and then the raw material has to be hauled from quarries to a crushing plant—i.e., the P symbol in Figure 2. After that, the raw material is crushed and then temporarily stored. Finally, the crushed (granular) material is hauled from the crushing plant to where is planned to be applied in the field, and in each stage, the material is poured and compacted. The variable defined as Xp (Figure 2) is used to measure the distance between the crushing plant and the location of the different quarries in the project.

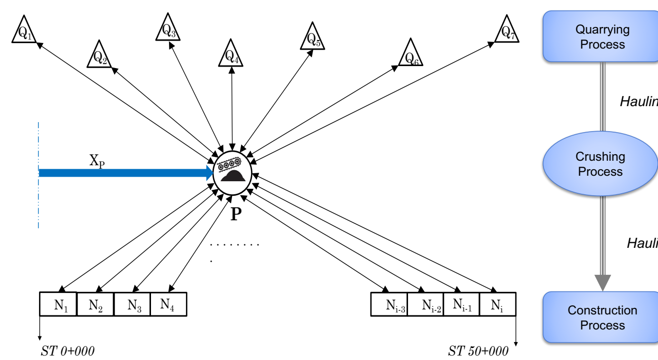

Figure 2 Model of the problem (own elaboration).

In the quarrying process, cost depends on equipment quantity and efficiency, geology, and explosives technology. That is why in the model, it is considered an average unit cost in $\$/m^3$. The hauling activities in real projects is a complex process that depends on truck quantity, time availability, roads topology, equipment efficiency, fuel consumption, and driver's expertise. In the model, two kinds of hauling are considered. The first one is the raw material hauling from quarries to crushing plant. In this case, the present project assumes that arc capacity is not restricted, so it simplified the hauling process considering one unloaded travel from the crushing plant to a quarry, and a second trip from the quarry to the crushing plant. (**Figure 3**)

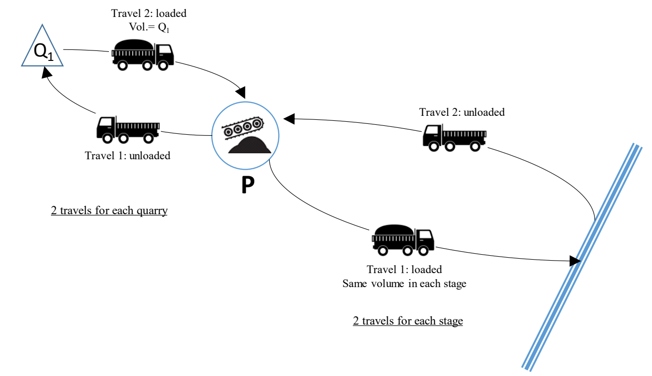

Figure 3 Hauling process detail in the model (Own elaboration).

The second type of hauling is the granular material hauling from the crushing plant to the construction field. As in the previous process, the project considers one travel loaded from crushing to the construction field and a second unloaded travel from the field to the crushing plant. (**Figure 3**) In this case, it is assumed that the same volume is hauled in all the arcs. The real profile of a highway has a mix of uphill and downhill sections, and consequently, this topology impacts the time and cost of hauling. In the present project, the highway analyzed has a permanent positive gradient of 1%, see as a reference (**Figure 4**). Finally, the base course studied has been modeled as a rectangular cross-section.

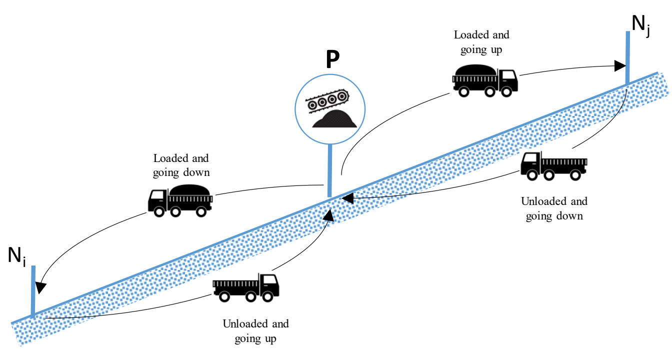

Figure 4 Impact of crushing plant location and hauling process (Own elaboration).

Therefore, the objective function proposed to minimize the base course construction cost is defined in equation 1.

Objective Function

$$Min\ \{Z\} = Quarrying\ Cost + Hauling\ raw\ material\ cost + Crushing\ cost + Hauling\ granular\ material + Base\ course\ collocation\ cost \quad (1)$$

The formulation of the costs of the five different sub-processes and the corresponding variables and constraints are defined as follow:

Quarrying Cost

The cost of the quarrying process is obtained by multiplying the total volume of the base course of the highway project by the unit cost of the quarrying process as shown in equation 2. As a special consideration for the calculation of the base course volume, a swell/shrinkage percentage was also included in the calculation of the total base course volume.

$$Quarrying\ cost = \frac{Shrink}{swell}\ factor \times Base\ Course\ Volume\ [m^3] \times quarrying\ unit\ cost\ \left(\$/_{m^3}\right) \quad (2)$$

Crashing Cost

For the crashing cost, the structure considers a rental cost and the cost of crushing the available base course material. Similarly to the previous structure, the base course volume is multiplied by a shrink/swell factor (Eq. 3).

$$Crushing\ cost = rent\ cost(\$) + \frac{Shrink}{swell}\ factor \times Base\ course\ volume\ [m^3] \times crushing\ unit\ cost\ \left(\$/_{m^3}\right) \quad (3)$$

Base course collocation cost

The cost of installing the base course in the highway is expressed as the total base course volume multiplied by the unit cost of such process (Eq. 4).

$$Base\ course\ collocation\ cost = Base\ course\ volume\ [m^3] \times\ collocation\ unit\ cost\ \left(\$/_{m^3}\right) \quad (4)$$

Hauling raw material cost

The cost of hauling raw material from the quarries to the crushing plant considers the cost of the entire transportation cycle. As such, the function includes a cost from the quarries to the crushing plant, but also the cost from the crushing plant to the quarries (Eq. 5). Considerations were made regarding the fact that the cost of returning to the quarries are lower since unloaded trucks are more fuel efficient than loaded trucks.

$$Hauling\ raw\ material\ cost = \sum_{i=1}^{7} X_{Q_iP} \times C_{Q_iP} + \sum_{i=1}^{7} X_{PQ_i} \times C_{PQ_i} \quad (5)$$

Where: X_{Q_iP} = distance from $quarry\ Q_i$ to P (crushing plant), C_{Q_iP} = hauling unit cost from $quarry\ Q_i$ to P (crushing plant), X_{PQ_i} = distance from P to $quarry\ Q_i$ and C_{PQ_i} = hauling unit cost from P to $quarry\ Q_i$.

Hauling Granular material cost

Similarly to the structure of hauling the raw material. In this case, hauling the granular material cost considers the cost of transporting the base course material from the crushing plant to the construction site (Eq. 6). Specifically, to the highway section that is under construction. To quantify the distance of each section under construction, the model discretizes the length of the highway in multiple nodes. For instance, in the case study described below, the length of the project was 50 kilometers, and the model used 1,000 nodes; therefore nodes were located every 50 meters. The main criteria to define the number of nodes was keeping a balance between practicality and the computational cost or solving the model.

$$Hauling\ granular\ material\ cost = \sum_{i=1}^{n} X_{PN_i} \times C_{PN_i} + \sum_{i=1}^{n} X_{N_iP} \times C_{N_iP} \quad (6)$$

Where: $X_{PN_i} =$ distance from crushing plant P to construction(node) N_i, $C_{PN_i} =$ hauling cost from crushing plant P to construction(node) N_i, $X_{N_iP} =$ distance from N_i to P and $C_{N_iP} =$ hauling cost from N_i to P.

Constraints

The constraints of the model, which aim to reflect the practical decision-making context of the problem, are presented. The first constraint is that the crushing plant to be installed in the project must be located within the boundaries of the project (Eq. 7).

$$Crushing\ Plant\ location\ \leq \text{length of the project} \quad (7)$$

The following constraint relates to the condition that the hauling volumes involved in the project must be lower or equal than the capacities of the quarries from the project. It is impossible to extract more than the capacity of the quarries (Eq. 8)

$$Hauling\ volume \leq Quarry\ Capacity \quad (8)$$

The next constraint related to the fact that the hauling volumes involved in the project must be greater than the volume required to build the project. Such assumption implies that the installation of base course material in the project will be exclusive from the material extracted from the quarries.

$$Hauling\ volume \geq Volume\ demanded\ by\ Project \quad (9)$$

The last constraint is that the variables related to the model cannot be negative (Eq. 10).

$$All\ values\ are\ nonnegative \quad (10)$$

Model Solution

For the solution of the proposed model, the next paragraph has a detailed description of how the authors got the results, specifically the results of the case study presented in the next section.

The first step is to input data into the spreadsheet developed using MS Excel to implement the model (**Figure 5**). Data from the highway characteristics such as the length of the project, width, thickness of the base course, and swell/shrinkage factor had to be added as general information from the project. Additionally, the unit prices of the quarrying, crushing, hauling, and base course installation costs had also to be added. As showed in **Figure 5**, the decision variables were the hauling volume from each quarry to supply the required base course material for the project. After the input of the data, the user must choose an initial location for the crushing plant, as well as the initial quantity of nodes to discretize the length of the project.

Regarding solving the optimization problem, the Solver tool from MS Excel was used to obtain the solution. This tool allows solving linear and non-linear programming problems. In this case, since our problem is modeled as Linear Programming, the simplex method was adopted (**Figure 6**).

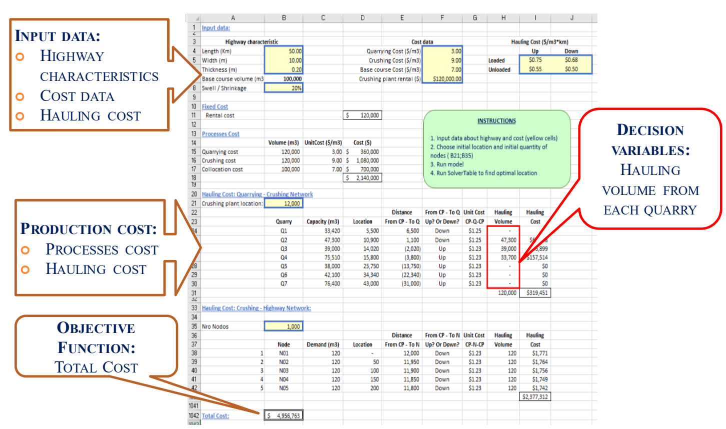

Figure 5 MS Excel interface to input data into the model (Own elaboration)

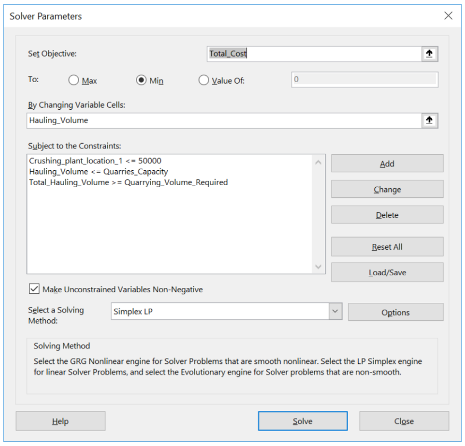

Figure 6 MS Excel interface to solve the optimization problem using the Simplex method (From using MS Excel).

3. Case study

The following case study has the intention to illustrate how the proposed model and methodology work using data from a real construction project. The project used as a case study corresponds to a highway construction project located in Arequipa, a southern city of Peru. General characteristics from the project that are relevant to the formulation of the problem are the following:

- Total length=50km
- Volume required (Base course) =100,000 m3
- Roadway width: 10m
- Base course thickness: 0.20m
- Swell=Shrinkage=20%
- Permanent 1% Gradient from start to end (ST 0+000 to ST 50+000)
- Crushing plant rental cost($): 120,000
- Quarries location and capacity (**Table 1**)
- Unit costs of the processes (**Table 2**)

The amount of base course material required for each node of the model was assumed as uniform, and calculated based on the following expression:

$$\text{Volume in each node} = \frac{\text{Total Volume (Base course)}}{\text{Number of nodes}} \quad (8)$$

As part of the modeling process, the numbers of nodes in the highway were gradually increased to assess the sensibility of the model regarding the number of nodes. In regards to the structure of the capacity of the quarries in the project, the unit costs in the case study the values for the different structures of the costs can be seen in **Tables 1-3.**

Table 1 Quarries capacity and location (Own elaboration).

Item	Stage	Capacity (m^3)
1	05+500	33,420
2	10+900	47,300
3	14+020	39,000
4	15+800	75,510
5	25+750	38,000
6	34+340	42,100
7	43+000	76,400

Table 2 Unit costs of processes (Own elaboration).

Process	Unit Cost ($/m3)
Quarrying cost	3.00
Crushing cost	9.00
Base course cost	7.00

Table 3 Hauling costs for different conditions (Own elaboration).

	Positive gradient ($/m3*km)	Negative gradient ($/m3*km)
Loaded	$0.75	$0.68
Unloaded	$0.55	$0.50

Consequently, taken into account all the information presented about the model structure and information from the project used as a case study. The structure of the five different sub-processes that are part of the optimization model are the following:

a) $Quarrying\ cost = 120{,}000m^3 \times quarrying\ unit\ cost\ \left(^{\$}/_{m^3}\right)$

b) $Crushing\ cost = rent\ cost(\$) + 120{,}000m^3 \times crushing\ unit\ cost\ \left(^{\$}/_{m^3}\right)$

c) $Base\ course\ collocation\ cost = 100{,}000m^3 \times collocation\ unit\ cost\ \left(^{\$}/_{m^3}\right)$

d) $Hauling\ raw\ material\ cost = \sum_{i=1}^{7} X_{Q_iP} \times C_{Q_iP} + \sum_{i=1}^{7} X_{PQ_i} \times C_{PQ_i}$

X_{Q_iP}: $distance\ from\ quarry\ Q_i\ to\ P\ (crushing\ plant)$
C_{Q_iP}: $hauling\ cost\ from\ quarry\ Q_i\ to\ P\ (crushing\ plant)$
X_{PQ_i}: $distance\ from\ P\ to\ quarry\ Q_i$
C_{PQ_i}: $hauling\ cost\ from\ P\ to\ quarry\ Q_i$

e) $Hauling\ granular\ material\ cost = \sum_{i=1}^{n} X_{PN_i} \times C_{PN_i} + \sum_{i=1}^{n} X_{N_iP} \times C_{N_iP}$

X_{PN_i}: $distance\ from\ crushing\ plant\ P\ to\ construction(node)\ N_i$
C_{PN_i}: $hauling\ cost\ from\ crushing\ plant\ P\ to\ construction(node)\ N_i$
X_{N_iP}: $distance\ from\ N_i\ to\ P$
C_{N_iP}: $hauling\ cost\ from\ N_i\ to\ P$

4. Results

This section includes the results of the optimization model presented in the section above. In addition to solving the problem from the case study, the following variations were considered: using a different number of nodes to discretize the model (e.g., from 10 to 1,000), the presence of more than one crushing plant in the project, and the extension length of the highway project. These variations were implemented to assess the sensitivity of the model results to these parameters.

4.1 Optimal Solution with one crushing plant and varying the number of nodes

Table 4 shows the optimal location from the crushing plant and the total cost using from 10 to 1,000 nodes for the 50 kilometers highway project respectively. It can be observed that the optimal location of the crushing plant varies as the number of nodes increase and the total cost as well. However, the variation is minimal. In terms of construction strategy purposes, discretizing the length of each section with 1,000 nodes, or 50 meters each one is considered detailed enough from a practical standpoint.

Table 4 Optimal location from the crushing plant and total cost using different numbers of nodes (own elaboration)

Number of Nodes	Sections Length (m)	Optimal Location	Total Cost (Minimum)
10	5,000m	15,400	$4,412,242
20	2,500m	15,400	$4,481,452
50	1,000m	15,400	$4,522,978
100	500m	15,600	$4,537,272
1,000	50m	15,800	$4,549,857

4.2 Optimal Solution with one crushing plant and varying the length of the project

Another potential variation related to the optimization of the base-course cost in a highway project is related to the length of the project. Therefore, a sensitivity analysis of the influence of the highway length on the optimized cost and location of the crushing plant was performed. **Table 5** shows the results of this sensitivity analysis varying the length of the project between 50 km to 100 km.

Table 5 Optimized Total Cost for Crushing plant location vs. Highway Length (own elaboration)

	50 Km	60 Km	70 Km	80 Km	90 Km	100 Km
15,000	4,579,028	6,352,826	8,468,105	11,003,303	13,866,185	17,104,650
15,200	4,559,580	6,333,383	8,448,667	10,983,872	13,836,462	17,063,026
15,400	4,550,412	6,324,222	8,439,512	10,974,723	13,817,017	17,031,682
15,600	4,550,016	6,323,832	8,438,259	10,970,102	13,803,920	17,009,110
15,800	**4,549,857**	**6,323,678**	8,435,043	10,954,988	13,784,933	16,986,775
16,000	4,549,937	6,323,764	**8,432,065**	10,940,110	13,766,193	16,964,679
16,200	4,550,255	6,324,088	8,429,324	10,925,472	13,747,688	16,942,820
16,400	4,560,249	6,334,088	8,436,259	**10,920,510**	**13,738,858**	16,930,638
16,600	4,579,920	6,353,766	8,452,871	10,925,226	13,739,702	16,928,134
16,800	4,599,830	6,373,681	8,469,722	10,930,178	13,740,787	16,925,867
17,000	4,619,977	6,393,834	8,486,812	10,935,370	13,742,114	**16,923,838**

Table 5, shows that the optimal location of crushing plant moves from 15,800 when the length of the project is 50 kilometers to 17,000 when the length is 100 kilometers. Notably, although the total distance is double, the total cost increases by approximately 3.7 times from $4,549,857 to $16,923,838. The primary cause to this disproportionate increase in the cost may be related to the fact that the location of the plant in the model from where the trucks transport the material to the field remained around the kilometers 15 and 17. As such, trucks need to travel long distances to transport materials to locations beyond the 50th kilometer, consequently, increasing the transportation cost.

4.3 Optimal Solution with two crushing plants

Another interesting variation to run with this model was a situation in which two crushing plants were installed in the construction project. The location of the two different crashing plants was set between the kilometers 14 and 16 for the first plant, and between the kilometers 34 and 36 for the second plant. **Table 6** shows the total cost for the different locations of the two different plants.

Table 6 shows that in this case, the minimum cost is $3,530,760, which occurs when the plants are located at kilometers 15.4 and 34.8. Notably, the total cost, in this case, is less than the total cost for the case of one crushing plant, which highlights the importance of the transportation cost of the base course material.

Table 6 Optimized total cost vs. Two Crushing Plant Locations (Own elaboration)

		Location from the second crushing plant										
		34,000	**34,200**	**34,400**	**34,600**	**34,800**	**35,000**	**35,200**	**35,400**	**35,600**	**35,800**	**36,000**
Location of the first crushing plant	14,000	3,596,164	3,594,567	3,590,180	3,583,370	3,577,371	3,579,792	3,584,317	3,588,843	3,594,106	3,600,108	3,606,110
	14,200	3,590,878	3,588,018	3,582,062	3,575,252	3,569,253	3,571,674	3,576,199	3,580,725	3,585,988	3,591,990	3,597,992
	14,400	3,584,329	3,579,756	3,573,800	3,566,990	3,560,991	3,563,412	3,567,937	3,572,463	3,577,726	3,583,728	3,589,730
	14,600	3,580,657	3,576,084	3,570,128	3,563,318	3,557,319	3,559,740	3,564,265	3,568,791	3,574,054	3,580,056	3,586,058
	14,800	3,583,645	3,579,072	3,573,116	3,566,306	3,560,307	3,562,728	3,567,253	3,571,779	3,577,042	3,583,044	3,589,046
	15,000	3,577,234	3,572,661	3,566,705	3,559,895	3,553,896	3,556,317	3,560,842	3,565,368	3,570,631	3,576,633	3,582,635
	15,200	3,560,878	3,556,305	3,550,349	3,543,539	3,537,540	3,539,961	3,544,486	3,549,012	3,554,275	3,560,277	3,566,279
	15,400	3,554,098	3,549,525	3,543,569	3,536,759	**3,530,760**	3,533,181	3,537,706	3,542,232	3,547,495	3,553,497	3,559,499
	15,600	3,556,192	3,551,619	3,545,663	3,538,853	3,532,854	3,535,275	3,539,800	3,544,326	3,549,589	3,555,591	3,561,593
	15,800	3,559,024	3,554,451	3,548,495	3,541,685	3,535,686	3,538,107	3,542,632	3,547,158	3,552,421	3,558,423	3,564,425
	16,000	3,561,856	3,557,283	3,551,327	3,544,517	3,538,518	3,540,939	3,545,464	3,549,990	3,555,253	3,561,255	3,567,257

5. Discussion

The results of this study suggest the importance of the level of detail in which the length of the highway project is discretized, in other words, the number of nodes used to model the highway. The more nodes are used to describe the highway; the more detailed is the estimated cost of the process. Nonetheless, there must be a balance between how detailed the model needs to be, and the level of practicality to implement the results. Not because the model can use thousands or millions of nodes to find the optimal solution it means is necessary to use such amount of nodes. Moreover, there is a computational cost to do so that in practice becomes more time waiting for the solution of the model. From a practical standpoint, if using hundreds or one thousand nodes the model provides an optimal solution with adequate accuracy for engineers, consequently that alternative should be valid and used. In the case of our study, we suggest that using one thousand nodes to model the project, which means a distance of 50 meters between nodes, it balances detailed information for the model and practicality for engineering decision making. Our findings and recommendations in this regard are aligned with existing literature in the sense that the information that the model generates must be useful and provide insight to engineers and decision makers dealing with the problem of earthworks to make the best decision possible with the information available (Lima et al., 2012; Marzouk and Moselhi 2004).

In regards to the influence of the length of the project on the optimal solution, in the case study explored, it was interesting to observe that having a project with the double of length, the cost of such project increased approximately 3.7 times. This finding showed a non-proportional relationship between project length and optimal transportation cost. Moreover, this finding emphasized the relevance of the location of the crushing plant in the project, which in our case was limited to be within the first fifty kilometers of the project, thus the longer the project, the longer the distance that trucks had to travel to transport the base course material and with that the cost of transportation. Based on this finding, we explored the impact of having a second crushing plant in the project. Notably, when adding a second crushing plant to the model, the total cost decreases considerably, in fact, this case reported the lowest optimal cost from all the results presented in this study. This finding reflects that the main component of the model is the cost of the travels between the crushing plant and the final destination in the field. With just one plant, the travels for the trucks that have to go far from the plant are more expensive, because these involve a longer distance. However, adding another crushing plant to the project means that the distances that trucks must travel are minimized, and as such, the total cost of transportation.

Finally, it is important to highlight that as members from the Architectural, Engineering, and Construction industry is always necessary to look for new alternatives and methods to study and deal with the problems in our industry from a scientific standpoint. However, it is also essential to take into account the practicality of the solutions and methods to be implemented during construction projects. That is why studies that combine a robust scientific formulation in the development and solution of the optimization model, but also the use of information and data from real construction projects are relevant to the field. Showing that reaching that equilibrium point between science and practicality is possible, may encourage the development of this type of studies in the future in our community, and also may be used as complementary material while teaching construction engineering and management courses.

6. Conclusions

This paper presents an optimization model based on linear programming of the cost of transportation for base-course material during the construction phase for highway projects. Specifically, the model considered the costs of extracting the base course materials, transporting the material to the crushing plant, crushing the material, transporting and installing the material in the field. The proposed model is implemented in a numerical case study project in South America, namely Peru. Based on the implementation of the model, the influence of how the project length is discretized, where the crushing plant is located, and how many crushing plants are used in the project, are discussed.

The findings from this study emphasize the relevance of the location of the crushing plant during a highway construction project regarding the transportation costs of base course material. Such relevance was corroborated by adding more crushing plants to the project of the case study, and as such, the total cost of transporting the base course material decreased, it was the lowest transportation cost reported in this study. Therefore, knowledge of the relevance of where to locate the crushing plant in the field, and practical tools to calculate the costs associated with the transportation of base course material can help decision-makers in planning earthworks for a highway project. One limitation of this study is the linear structure from the model costs, and in reality, these relationships may be non-linear. However, such non-linearity would require higher and more expensive computational power. Future work can investigate accounting for non-linear cost structures of the model and include variability to the input parameters to address uncertainty considerations as part of improving the proposed model.

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