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EARTHWORKS PLANNING USING OPTIMIZATION TECHNIQUES: LITERATURE ANALYSIS AND SOLUTION PROPOSAL

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Dissertação apresentada ao Programa de Pós-Graduação em Engenharia de Transportes do Centro de Tecnologia da Universidade Federal do Ceará, como requisito parcial à obtenção do título de mestre em Engenharia de Transportes. Área de Concentração: Infraestrutura de Transportes

Orientador: Prof. Dr. Ernesto Ferreira Nobre Júnior

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ABSTRACT

Earthmoving operations account for approximately one-third of construction costs in large engineering projects and require efficient resources management. Since the 1980s, researchers have suggested computational optimization techniques to improve decision-making in earthworks and proposed mathematical models for material and equipment allocation. However, these computational applications are generally ignored by road construction professionals, who plan earthworks through estimations based on mass haul diagrams. Consequently, this dissertation has the objective of investigating the usage of optimization techniques in earthmoving operations to propose a novel mathematical programming approach for cost minimization on road construction projects. This research was divided into two distinct parts: A systematic mapping study and an original research article. At first, I presented a mapping study on the topic of optimization of earthmoving planning and operation. I analyzed 5,134 papers in total, selecting 72 relevant studies through consistent selection criteria. As a result, I could map the research field by identifying the most investigated subjects, optimization techniques, and research gaps. I found that allocation, fleet planning, routing, and scheduling problems were the most commonly explored topics, and linear programming, mixed-integer linear programming, and genetic algorithms were the most used optimization methods. I also observed that studies related to road construction have focused on improving well-known mathematical models, incorporating specific engineering features such as temporary haul roads, paving operations, and material mixing and recycling. Based on these research trends, I proposed a mixed-integer linear programming model to plan material allocation in earthmoving and paving operations, including geotechnical constraints and construction of haul roads. This optimization approach was validated by applying the model to a real road project with 121 cut sections, 257 fill sections, 272 pavement segments, 26 borrow pits, and five quarries. After structuring and modeling the proposed case study, I obtained the optimized solution in 2.98 seconds, indicating that realistic instances can be solved in reasonable processing times.

Keywords: Highway Engineering. Systematic Literature Review. Operations Research. Allocation Problem

RESUMO

Operações de terraplenagem correspondem a aproximadamente um terço dos custos de construção em obras de grande porte, exigindo uma gestão eficiente de recursos disponíveis. Como resposta, nos anos 1980, pesquisadores recomendaram o uso de técnicas computacionais de otimização como ferramenta na tomada de decisões em obras de terraplenagem, sendo propostos modelos matemáticos para alocação de materiais e maquinário. Contudo, os métodos sugeridos são geralmente ignorados por engenheiros rodoviários, que por sua vez planejam as obras com base em estimativas feitas a partir de diagramas de massa. Como consequência, essa dissertação tem o objetivo de investigar o uso de técnicas de optimização em obras de terraplenagem, bem como propor uma nova abordagem de programação matemática para minimização dos custos em projetos de rodovia. Essa pesquisa foi dividida em duas partes: Um mapeamento sistemático da literatura e um artigo original de pesquisa. Primeiramente, foi feito um mapeamento da área, onde foram analisados 5134 artigos da qual foram selecionados 72 estudos considerados relevantes segundo os critérios de seleção. Com base nos resultados, foi possível identificar os tópicos mais pesquisados, as técnicas de otimização utilizadas e as principais lacunas do campo de pesquisa. Em resumo, os problemas de alocação de materiais, planejamento de frota, roteamento e planejamento do tempo foram os temas mais estudados, enquanto programação linear, programação linear inteira mista e algoritmos genéticos foram as técnicas de otimização mais utilizadas pelos autores. Também foi observado que estudos relacionados a projetos rodoviários possuem maior foco no melhoramento de modelos já existentes, onde novos aspectos construtivos são incorporados, tais como caminhos de serviço, operações de pavimentação, mistura de diferentes materiais e reciclagem. De acordo com essas tendências de pesquisa, foi proposto um modelo baseado em programação linear inteira mista para planejamento da alocação de materiais em operações de terraplenagem e pavimentação, incluindo restrições geotécnicas e construção de caminhos de serviço. O modelo foi validado com dados de um projeto rodoviário real com 121 seções de corte, 257 seções de aterro, 272 segmentos de pavimentação, 26 empréstimos e cinco jazidas. Após estruturação e aplicação do estudo de caso, o problema proposto apresentou a solução otimizada em 2.98 segundos, sendo possível concluir que o modelo tem capacidade de processar instâncias reais em um curto intervalo de tempo.

Palavras-chave: Engenharia Rodoviária. Revisão Sistemática da Literatura. Pesquisa Operacional. Problema de Alocação.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

AHP	*Analytical Hierarchy Process*
CAPES	*Coordination for the Improvement of Higher Education Personnel*
DNIT	*National Department of Transportation Infrastructure*
GIS	*Geographic Information System*
GPS	*Global Positioning System*
HMA	*Hot Mix Asphalt*
LCRCFSP	*Least-cost Route Cut and Fill Sequencing Problem*
LP	*Linear Programming*
MILP	*Mixed-integer Linear Programming*
MIQP	*Mixed-integer Quadratic Programming*
RIS	*Research Information Systems*
SICRO	*System of Referential Construction Costs*
SRCFP	*Shortest Route Cut and Fill Problem*
StArt	*State of the Art through Systematic Review*
STSP	*Symmetric Traveling Salesman Problem*
TRNDP	*Temporary Road Network Design Problem*

SUMMARY

1 INTRODUCTION

1.1 Presentation

Earthmoving operations can be defined as construction works that are developed aiming to shape the natural field, fulfilling specifications of an engineering project, including a diverse set of activities - such as excavation, loading, grading, and compaction (PRATA *et al.*, 2008). As a consequence, earthmoving operations are one of the most expensive construction stages (20-30% of total construction costs) (HARE *et al.*, 2011; LIU *et al.*, 2013), demanding a large amount of heavy equipment and qualified labor. Thus, these operations need to be efficiently planned to rationally allocate resources and reduce any possible additional expense.

In the early 1980's, researchers began to propose and solve earthmoving management problems through optimization techniques. The first computationally implemented optimization methodology was introduced by Mayer and Stark (1981). They used a *Linear Programming* (LP) model to move the soil from cut sections to fill sections with a minimum total allocation cost. As a result, they concluded that operations research is a powerful construction planning tool, being a potential alternative to conventional methods.

After Mayer and Stark (1981), many authors have expanded the optimization approaches to other areas related to earthmoving operations. In general, they introduced new models and algorithms for planning equipment allocation, operations routing and project scheduling. For instance, Marzouk and Moselhi (2002) developed a genetic algorithm meant to choose the least costly equipment fleet while Henderson *et al.* (2003) utilized a simulated annealing algorithm to calculate the shortest truck route for cut-and-fill allocations. On the other hand, Lin *et al.* (2012) presented a genetic algorithm that generates and selects truck fleet schedules.

Although authors propose new approaches for the topics mentioned above, many road construction professionals ignore numeric methods, primarily using mass-haul diagrams for planning material allocation and subsequently making decision related to routes and equipment usage. Essentially, mass-haul diagrams are graphical representations of the cumulative soil volume along the road, being used to calculate tradeoffs between cut and fill sections. However, mass-haul diagrams present some limitations to their efficient use in large projects, generating additional costs. For instance, mass-haul diagrams are imprecise in situations where the soil characteristics vary along the road (e.g., shrinkage and swell factors, and bearing capacity) and where earth allocation costs are not proportional to haul distances (MAYER; STARK, 1981;

LIMA *et al.*, 2013; MESQUITA, 2012).

1.2 Research Gap

As previously mentioned, optimization methods are not widely utilized in road construction planing. Consequently, the existing optimization applications need to be deeply analyzed to evaluate why they are not primarily considered by engineers.

As a hypothesis, I assumed that most models are not totally adapted to road construction projects, overlooking important construction features such as geotechnical conditions, construction of temporary haul roads and paving operations. Even thought some authors introduced distinct solutions to these construction specificities, these solutions do not seem to be integrated, limiting their usage in such scenarios. Therefore, I inferred that relevant research on optimization of earthmoving operations should be systematically mapped to evaluate the possible research directions to develop a optimization model more suitable to road construction applications, integrating new and existing modeling solutions.

1.3 Research Questions

Based on the presented research gap, I was able to formulate the main research questions of this study, listed as follows:

- *MRQ1*: Why are optimization techniques not primarily utilized for planning real-world earthmoving projects?
- *MRQ2*: Is it possible to develop an optimization model for minimizing earthmoving costs on road projects considering several construction specifications?
- *MRQ3*: Is this optimization approach capable of solving realistic instances?
- *MRQ4*: Is this optimization approach computationally expensive?

1.4 Objectives

I need to accomplish the following research objectives to answer the main research questions:

1.4.1 General Objective

My general objective is to develop an optimization model for minimizing the costs of earthmoving operations on road construction, considering distinct project requirements as modeling constraints (geotechnical specifications, paving operations and temporary haul road construction).

1.4.2 Specific Objectives

- Systematically map the literature and integrate research contributions, investigating how optimization techniques are being used on construction projects;
- Evaluate the model applicability to real-world road projects;
- Analyze the computational performance of the proposed model.

1.5 Structure

Complying with the research objectives, this dissertation is divided into two different articles. First, following a consistent systematic review methodology, I elaborated an in-depth literature analysis of research on optimization of earthmoving planning and operation. Based on my first findings, I presented an article with original research that proposes a *Mixed-integer Linear Programming* (MILP) allocation model for earthmoving and paving operations, including constraints related to geotechnical specifications and temporary haul road construction.

In the first article, the review methodology is based on the instructions of Kitchenham and Charters (2007) and Felizardo *et al.* (2017) that recommended the creation of research questions for the development of an effective search strategy. Consequently, it is worth emphasizing that these research questions are not related to the main research questions (*MRQ1* to *MRQ4*) previously presented in Section 1.3.

2 OPTIMIZATION OF EARTHMOVING PLANNING AND OPERATION: A MAPPING STUDY

2.1 Abstract

This article presents a mapping study of the research on the optimization of earthmoving planning and operation. Its goal is to investigate relevant papers and characterize the field by identifying the most commonly explored topics, optimization techniques, and research trends. I applied a systematic review approach based on automatic searches and snowball sampling to select relevant papers on earthwork optimization. Our searches retrieved 5,134 results, from which I selected 72 papers between 1958 and 2019. I found that allocation, fleet planning, routing, and scheduling problems were the most commonly investigated topics, and linear programming, mixed-integer linear programming, and genetic algorithms were the most usually used optimization techniques. I also observed that most models that considered construction factors reported improvements in construction budgets or hauling plans. However, I found few studies demonstrated the impact of earthwork optimization after the planning and pre-construction stages. Furthermore, a limited number of papers presented the advantages of earthwork optimization for reducing the environmental impacts in construction.

2.2 Introduction

Earthworks account for approximately 20–30% of total construction costs (HARE *et al.*, 2011; LIU *et al.*, 2013) and demand qualified labor, suitable equipment, and rational allocation of resources. Consequently, managers must make decisions about various construction-related matters to execute earthwork projects efficiently and inexpensively. For example, managers need to know the optimal set of equipment, the most economical cut and fill configurations, and the appropriate sequences, routes, and schedules for earthmoving operations. Therefore, the use of operational research techniques has been proposed to solve these management problems using mathematical programming, simulation-optimization systems, and metaheuristic algorithms (FALCÃO *et al.*, 2016).

Although many authors have developed mathematical models of earthmoving, few studies (FALCÃO *et al.*, 2016; NASKOUDAKIS; PETROUTSATOU, 2016) have integrated these contributions and analyzed the real benefits of using optimization in construction. Therefore, this paper presents a mapping study of research on optimization techniques applied in earthmoving planning and operation and characterizes the research field to identify gaps and trends. Furthermore, this paper also identifies the main topics and objectives, contribution types, research types, and outcomes of selected studies.

In contrast to other literature reviews (FALCÃO *et al.*, 2016; NASKOUDAKIS; PETROUTSATOU, 2016), this study used a systematic methodology with an exclusive focus on earthmoving. I applied a high-sensitivity approach with the objective of analyzing the largest possible number of studies, using a solid strategy to search for and select relevant papers. Our searches of seven online databases were based on automatic methods and snowball sampling. As a result, this study reviewed more than 5,000 search results, including 1,435 references and 891 citations from backward and forward snowball sampling.

The remainder of this paper is structured as follows. In Section 2.3, I describe earlier work, including a previous investigation of secondary studies. In Section 2.4, I present the review method, including the research questions, inclusion and exclusion criteria, data sources, and search strategy. In Section 2.5, I analyze the search results and consider the implications, outcomes, and limitations of this review. Finally, I draw conclusions based on the results and present suggestions for future research (Section 2.6).

2.3 Background

Earthwork optimization was a priority in the early development of operations research. According to Falcão *et al.* (2016), the mathematical approach of Kantorovitch (1958), which was developed in the early 1940s, was the first to be applied to earthmoving operations. Kantorovitch (1958) proposed a mathematical model for allocating earth volumes with the lowest total expense considering the unit cost of transporting 1 m^3 of earth from a start point to a final destination. Additionally, he also presented the conditions for volume balance, where the sum of the masses must be the same before and after leveling.

Further approaches to earthwork optimization were not proposed until the late 1970s, after considerable progress in numerical methods and the popularization of microcomputers (CALHOUN, 1981; DU *et al.*, 2009). For example, Easa (1987) noted that the first *Linear Programming* (LP) model of earth allocation was suggested by Stark and Nicholls (1972) in 1972 and later developed by Mayer and Stark (1981) in 1981.

Mayer and Stark (1981) demonstrated an innovative programming approach. Their study, as noted by Lima *et al.* (2013), was the first to incorporate construction characteristics into the mathematical constraints. For instance, their model incorporated shrinkage factors, borrow pits, and disposal sites.

Subsequent research has considered increasingly complex engineering operations. For example, Jayawardane and Harris (1990) added constraints related to the project duration to an earth allocation model; Marzouk and Moselhi (2002) developed an algorithm for equipment fleet selection, and Henderson *et al.* (2003) introduced a mathematical approach to minimize the earthwork equipment route. Researchers have also integrated optimization with other computational technologies, such as discrete-event simulation (JAYAWARDANE; PRICE, 1994a), *Global Positioning System* (GPS) tracking (MOSELHI; ALSHIBANI, 2007a), and *Geographic Information System* (GIS) visualization (LIAO *et al.*, 2016). As mentioned in Section 2.2, many studies have proposed optimization solutions for earthmoving planning and operation, especially in the last 20 years. However, few studies have linked the modeling contributions or analyzed the possible effects of using optimization in daily earthwork operation. Using systematic searches, I found that only two studies (FALCÃO *et al.*, 2016; NASKOUDAKIS; PETROUTSATOU, 2016) have evaluated the research trends and outcomes to characterize this field through literature surveys.

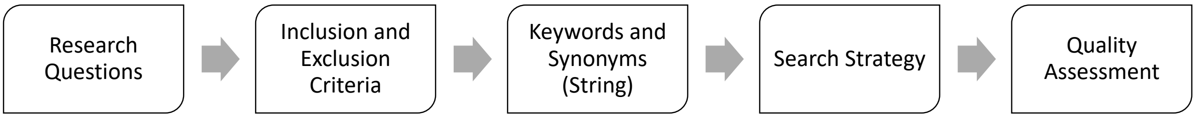
First, Naskoudakis and Petroutsatou (2016) conducted a thematic review of the main research on the construction equipment used in earthwork. The authors selected 73 papers from four online databases, choosing papers related to equipment fleet planning, equipment maintenance, and automation/robotics. However, they did not focus on mathematical programming, instead covering the optimization of equipment fleet selection in a section of their review.

Unlike Naskoudakis and Petroutsatou (2016), Falcão *et al.* (2016) emphasized the optimization techniques applied to earthmoving and highway construction, considering papers about transportation, scheduling, and routing problems. They analyzed 48 papers, sorting them by objective (e.g., cost minimization, duration minimization, and quality maximization) and optimization techniques (e.g., LP, dynamic programming, and genetic algorithms). The authors also presented a thorough discussion of mathematical modeling of earthmoving and highway construction, including the contributions, criticisms, and impacts of each optimization technique. However, they did not use a systematic approach to paper selection, instead restricting the survey to a limited range of primary studies.

2.4 Review Methodology

I performed a systematic mapping study of earthwork optimization on the basis of the guidelines of Kitchenham and Charters (2007) and the recommendations of Felizardo *et al.* (2017). Although these procedures are focused on software engineering, it was possible to employ the steps to conduct an adequate and unbiased literature review. Consequently, I developed a research protocol that includes the research questions, inclusion and exclusion criteria, keywords and synonyms, search strategy, and quality assessment (Figure 1).

Figure 1 – Mapping study planning stage



Source: Author

2.4.1 Research Questions

According to the mapping study objectives, two main research questions (RQs) were formulated to guide the search procedures and results:

- *RQ1*: What are the main topics studied in research related to earthmoving optimization problems?
- *RQ2*: What are the research goals of employing optimization techniques in earthmoving planning and operation?

Following Felizardo *et al.* (2017) and the mapping studies of Souza *et al.* (2014) and Cruz *et al.* (2015), I created specific questions based on the characteristics of the selected studies, highlighting subjects such as the contribution type, research type, research focus, type of publication, and outcomes, as follows:

- *RQ3* (Contribution type): What optimization techniques are used to solve earthmoving optimization problems?
- *RQ4* (Research type): What types of research have been conducted?
- *RQ5* (Research focus): What is the target audience of this research (academia or industry)?
- *RQ6* (Type of publication): When and where were the studies published?
- *RQ7* (Outcomes): What were the main outcomes of using optimization techniques in earthmoving?

To answer question *RQ4*, I used the system for classification of research approaches presented by Wieringa *et al.* (2005) and the definitions of Petersen *et al.* (2008), as shown in Table 1:

Table 1 – Research types

Category	Definitions
Evaluation papers	- Evaluation of technique in different situations; - How this technique is being implemented; - Identification of consequences, benefits and limitations.
Experience papers	- How an approach has been done in practice; - Case studies; - Personal experience of the author.
Opinion papers	- Personal opinions on whether some technique is good or bad; - How something should be done.
Philosophical papers	- Taxonomy; - Conceptual framework.
Solution proposal	- Solution to a certain problem; - Novel approach or extension of an existing technique; - Validation of a solution using an example.
Validation research	- Investigation of a technique not yet implemented.

Source: Author.

2.4.2 Inclusion and Exclusion Criteria

The selection criteria were classified as an inclusion criterion (IC) and exclusion criterion (EC), according to the selection parameters of Souza *et al.* (2014). I considered only a general inclusion criterion based on the research objective of broadly characterizing this research field:

- *IC1*: Studies that applied, compared, or analyzed optimization techniques used for earthmoving planning and operation.

I also considered seven EC:

- *EC1*: The study is not written in English.
- *EC2*: The study was published only as an abstract.
- *EC3*: The study is an older version of other studies already considered.
- *EC4*: The study is not a primary or secondary study, but rather an editorial, summary of a keynote, workshop, or tutorial.
- *EC5*: The study does not present optimization techniques.
- *EC6*: The study problem is not directly related to earthmoving planning and operation.
- *EC7*: It was not possible to access the full text.

To elucidate the selection parameters in this mapping study, I incorporated the following considerations into the presented EC:

- Criterion *EC4* also excluded books, chapters, thesis, and dissertations owing to their length and format, which would hinder full-text reading.
- Criterion *EC5* was not applied to secondary studies on earthwork optimization problems.
- Studies on the mechanical components of earthwork equipment, specific applications of mining engineering, and road alignment design were excluded by criterion *EC6*. As an example, the studies of Hare *et al.* (2014) and Mondal *et al.* (2015) considered earth allocation costs in road design. However, the main contributions were related to optimization of vertical and horizontal alignments.

2.4.3 Keywords and Synonyms

This mapping study aims to analyze as many studies as possible. Therefore, I considered synonyms, related terms, and variants of the keywords “earthmoving” and “optimization,” as shown in Table 2.

Table 2 – Search terms

Keywords	Synonyms /Related Terms/Variants	
Earthworks	- Cut and fill; - Cut-and-fill; - Earth moving; - Earthmoving; - Earthwork; - Earthworks.	
Optimization	- Mathematical model; - Mathematical modeling; - Mathematical programming; - Maximisation; - Maximization; - Maximising; - Maximizing; - Minimisation; - Minimization;	- Minimising; - Minimizing; - Operational Research; - Operations Research; - Optimisation; - Optimization; - Optimising; - Optimizing.

Source: Author.

To perform a mapping study based on automatic online searches, I built a search string using the search terms in Table 2. I used two logical operators, "OR"and "AND". The operator "OR"indicated that at least one of the search terms must appear in the title, abstract, or keywords. By contrast, the term "AND"indicated that both search terms must appear. In some databases, it was possible to use the operator "*"to identify semantic variations. Furthermore, no date range was specified, as shown in Table 3.

Table 3 – Search strings

Search String 1	("Earth Moving"OR "Earth-moving"OR "Earthmoving"OR "Earthwork" OR "Earthworks"OR "Cut and Fill"OR "Cut-and-fill") AND ("Mathematical Modeling"OR "Mathematical Programming" OR "Mathematical Model"OR "Maximisation"OR "Maximization"OR "Maximising"OR "Maximizing" OR "Minimisation"OR "Minimising"OR "Minimization" OR "Minimizing"OR "Operational Research" OR "Operations Research"OR "Optimisation"OR "Optimising" OR "Optimization"OR "Optimizing")
Search String 2 (with *)	("Earth Moving"OR "Earth-moving"OR "Earthmoving"OR "Earthwork*" OR "Cut and Fill"OR "Cut-and-fill") AND ("Mathematical Programming" OR "Mathematical Model*"OR "Maximi* "OR "Minimi* "OR "Operational Research"OR "Operations Research"OR "Optimi*")

Source: Author.

Following the guidelines of Kitchenham and Charters (2007), I checked the search string against a list of known studies. The primary studies were taken from the survey of Falcão *et al.* (2016), which is the only literature review that highlights earthwork optimization. However, I excluded the articles in Falcão *et al.* (2016) related to highway construction planning, considering only studies directly related to earthmoving. All the papers were found in the first trial, as shown in Table 4 , demonstrating that the research string was satisfactory for this mapping study.

Table 4 – Results of test search

Authors	Title
Nandgaonkar (1981)	*Earthwork Trasportation Allocations: Operations Research*
Mayer and Stark (1981)	*Earthmoving Logistics*
Easa (1987)	*Earthwork Allocations with Nonconstant Unit Costs*
Christian and Caldera (1988)	*Earthmoving Cost Optimization by Operational Research*
Easa (1988)	*Earthwork Allocations with Linear Unit Costs*
Jayawardane and Harris (1990)	*Further Development of Integer Programming in Earthwork Optimization*
Jayawardane and Price (1994a)	*A New Approach for Optimizing Earth Moving Operations. Part I*
Jayawardane and Price (1994b)	*A New Approach for Optimizing Earth Moving Operations. Part II*
Henderson *et al.* (2003)	*Solving the Shortest Route Cut and Fill Problem Using Simulated Annealing*
Lim *et al.* (2005)	*Tabu Search Embedded Simulated Annealing for the Shortest Route Cut and Fill Problem*
Moselhi and Alshibani (2009)	*Optimization of Earthmoving Operations in Heavy Civil Engineering Projects*
Hare *et al.* (2011)	*Models and Algorithms to Improve Earthwork Operations in Road Design Using Mixed Integer Linear Programming*
Lima *et al.* (2013)	*Distribution of Materials in Road Earthmoving and Paving: A Mathematical Programming Approach*

Source: Author.

2.4.4 Search Strategy

2.4.4.1 Data Sources and Software

The search strategy used in this study was based on multiple automatic searches and a snowball sampling methodology. I used seven online databases, which are listed in Table 5.

Table 5 – Online databases used in this study

Source	Website
ACM digital library	<http://portal.acm.org>
CSA/ASCE Civil Engineering Abstracts (ProQuest)	<https://www.proquest.com>
Engineering Village	<http://www.engineeringvillage.com>
IEEEXplore Digital Library	<http://www.ieeexplore.ieee.org/Xplore>
ScienceDirect	<http://www.sciencedirect.com>
Scopus	<http://www.scopus.com>
Web of Science	<http://www.webofknowledge.com>

Source: Author.

I considered databases that allow keyword searches of three metadata fields (title, abstract, and keywords) and extraction of search results in BibTeX or *Research Information Systems* (RIS) files.

I selected the software *State of the Art through Systematic Review* (StArt), version 3.2 beta (FABBRI *et al.*, 2016), as a systematic review assistant because it can manage references using bibliographic files (BibTeX and RIS) and sufficiently fulfills all the requirements of this mapping study. According to Felizardo *et al.* (2017) analysis (Table 6), this software is one of the few packages that can assist authors in developing a protocol, conducting study selection, and creating research reports.

Table 6 – Systematic review software

Functions/Tools	SLuRp	StArt	SLR-Tool	SLRTOOL
Protocol development		✓	✓	
Automatic search support		✓		
Study Selection	✓	✓	✓	✓
Quality assessment	✓	✓	✓	✓
Data extraction	✓	✓	✓	✓
Meta-analysis	✓			
Research report	✓	✓	✓	

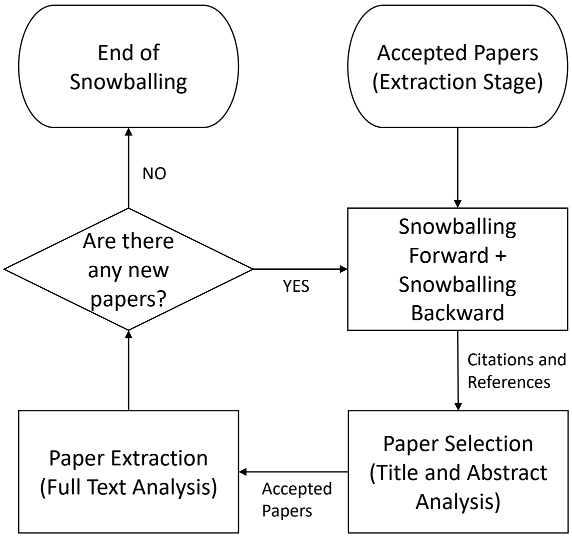
Source: Fabbri *et al.* (2016) and Felizardo *et al.* (2017).

2.4.4.2 Pre-selection, Selection, and Snowball Sampling

As mentioned in Section 2.4.4.1, I conducted automatic searches of each database listed in Table 5. Subsequently, pre-selection was performed according to the mapping methodology of Souza *et al.* (2014) and Cruz *et al.* (2015). In brief , I removed duplicate papers and then evaluated all the titles and abstracts for inclusion or exclusion according to the criteria described in section 2.4.2. Next, in the selection stage, I analyzed the full texts of the selected papers using the same inclusion and exclusion criteria as in pre-selection. Then I applied snowball sampling to the extracted studies.

In the snowball sampling stage, I used the reference lists (snowball sampling backward) and citations (snowball sampling forward) of the selected papers to identify additional relevant studies. Following the approach of Wohlin (2014), I used the reference lists and citation records in the databases listed in Table 5. Next, I applied the pre-selection and selection procedures to these additional papers. The procedures were repeated using the newly extracted articles until no more studies were selected, as shown in Figure 2.

Figure 2 – Snowball sampling procedure



Source: Author

2.4.5 Quality Assessment

The quality assessment was based on the evaluation questions (*EQs*) of the software engineering mapping study of Pedreira *et al.* (2015). I adopted the questions related to replicability, adaptability, and performance to evaluate our selected primary studies. As a result, these five questions were considered:

- *EQ1*: Does the study present models or algorithms that can be replicated in real-life earthmoving operations?
- *EQ2*: Does the model used in the study include engineering considerations (e.g., soil types, equipment specifications, field peculiarities, and excavation sequencing)?
- *EQ3*: Is the problem successfully represented by a model or algorithm?
- *EQ4*: Does the study present evidence of computational performance?
- *EQ5*: Does the study mention any positive effects of optimization in reducing the environmental impacts of earthmoving operations (e.g., reduction of greenhouse gas emissions or material recycling)?

To provide a numerical parameter for evaluating each subjective question, each question was classified by a Likert scale from 0 ("Not at all") to 5 ("Completely") as described by Pedreira *et al.* (2015).

2.5 Results and Discussion

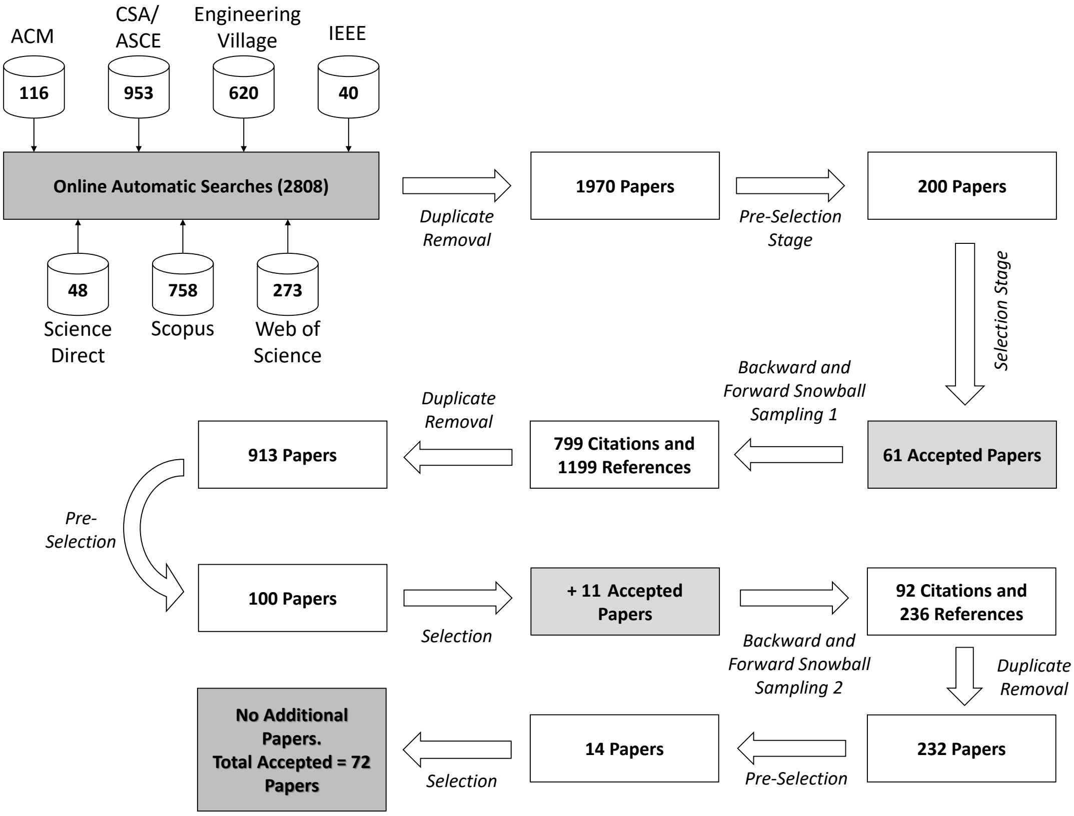
2.5.1 Search and Selection Results

I applied the search strategy based on automatic searches and snowball sampling of online databases (Table 5), which returned 5,134 results (2,808 entries + 799 citations and 1,199 references from snowball sampling 1 + 92 citations and 236 references from snowball sampling 2), which include 2,019 duplicated papers, 3043 rejected papers, and 72 accepted papers, as shown in Figure 3. I searched the online databases on January 14, 2020 . I searched for citations for the first snowball sampling procedure on May 8, 2020 and for the second snowball sampling procedure on May 16, 2020. However, only citations published before January 14, 2020, were considered.

Figure 3 shows that 72 papers (Appendix A) were selected from among 3115 unique papers. As a result, the study had a precision rate of 2.31% (DICKERSIN *et al.*, 1994), which is within an acceptable range compared to other mapping studies that used snowball sampling and generic search strings. For instance, Souza *et al.* (2014) and Cruz *et al.* (2015) reported precision rates below 4%.

Most of the papers rejected in the selection stage and snowball selection were rejected according to *EC5* (the study does not present optimization techniques) and *EC6* (the

Figure 3 – Search procedure

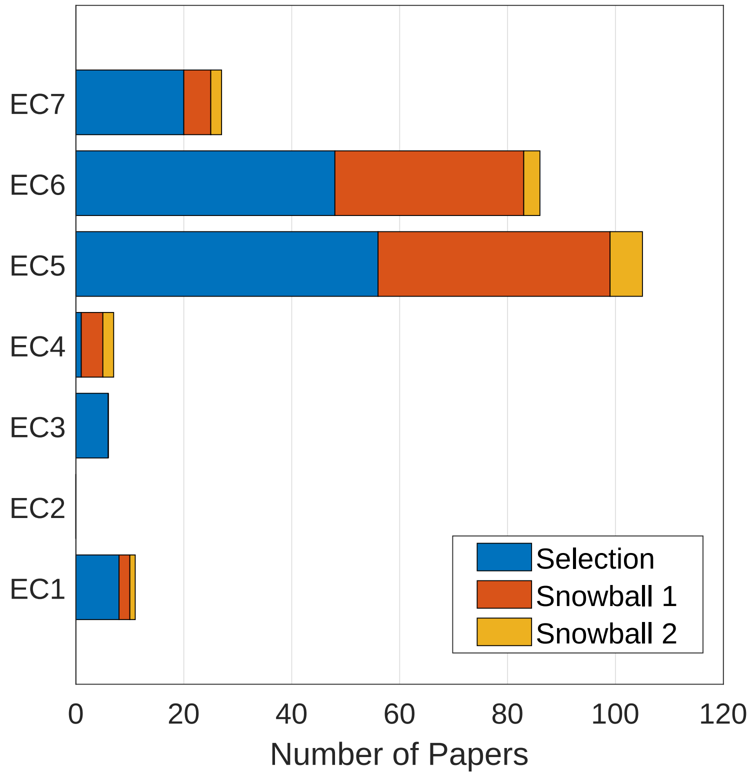


Source: Author

study problem is not directly related to earthmoving planning and operation), as shown in Figure 4. This result can be attributed to the fact that *EC5* and *EC6* are related to the content of the obtained papers. The papers excluded by *EC5* generally describe studies that applied other classes of numerical methods such as expert systems, simulation models, or data mining, but did not consider any type of optimization technique. In addition, some studies excluded by *EC5* also used inaccurate methods. For example, many studies proposed graphical techniques based on empirical data. In contrast to the studies rejected by *EC5*, those rejected by *EC6* used optimization techniques. However, they considered other problems such as road alignment design, specific topics in mining engineering, or scheduling models that managed earthworks as a generic stage of construction.

As shown in Figure 4, 27 papers were excluded by *EC7* (it was not possible to access the full text), even though access to database collections was guaranteed by the Brazilian *Coordination for the Improvement of Higher Education Personnel* (CAPES) (CAPES, 2020). Most of these papers were not available online and were published in unrecognized sources such as local conference proceedings, discontinued journals, or institutional papers. Furthermore, I also noticed that only a small number of papers (24/242 = 9.9%) were excluded by *EC1*, *EC2*,

Figure 4 – Number of papers rejected according to each selection criterion



Source: Author

EC3, and *EC4*, which demonstrates that most of the pre-selected papers were academic full-text papers originally written in English.

2.5.2 *Answers to the Research Questions*

In this section, I present the answers to the research questions described in Section 2.4.1 in order to satisfy the research objective of characterizing and mapping the research field. All the selected papers were listed and classified according to the characteristics evaluated in each research question, as shown in Appendix A.

2.5.2.1 *Research Question RQ1: What are the main topics studied in research related to earthmoving optimization problems?*

After the 72 selected full texts were analyzed, I classified earthwork optimization problems into four main research topics: earth allocation planning, equipment fleet planning, earthmoving operation routing, and earthmoving operation scheduling.

2.5.2.1.1 Earth Allocation Planning

Earth allocation can be defined as an optimization problem that aims to find the best combination of cut sections and fill sections. In engineering problems, cut sections are areas where there is more soil or rock than the planned elevation, which is hauled to fill sections or discarded in spoil pits. By contrast, fill sections are areas with insufficient material to reach the planned elevation, and material from cut sections or borrow pits is used to fill this volume deficit.

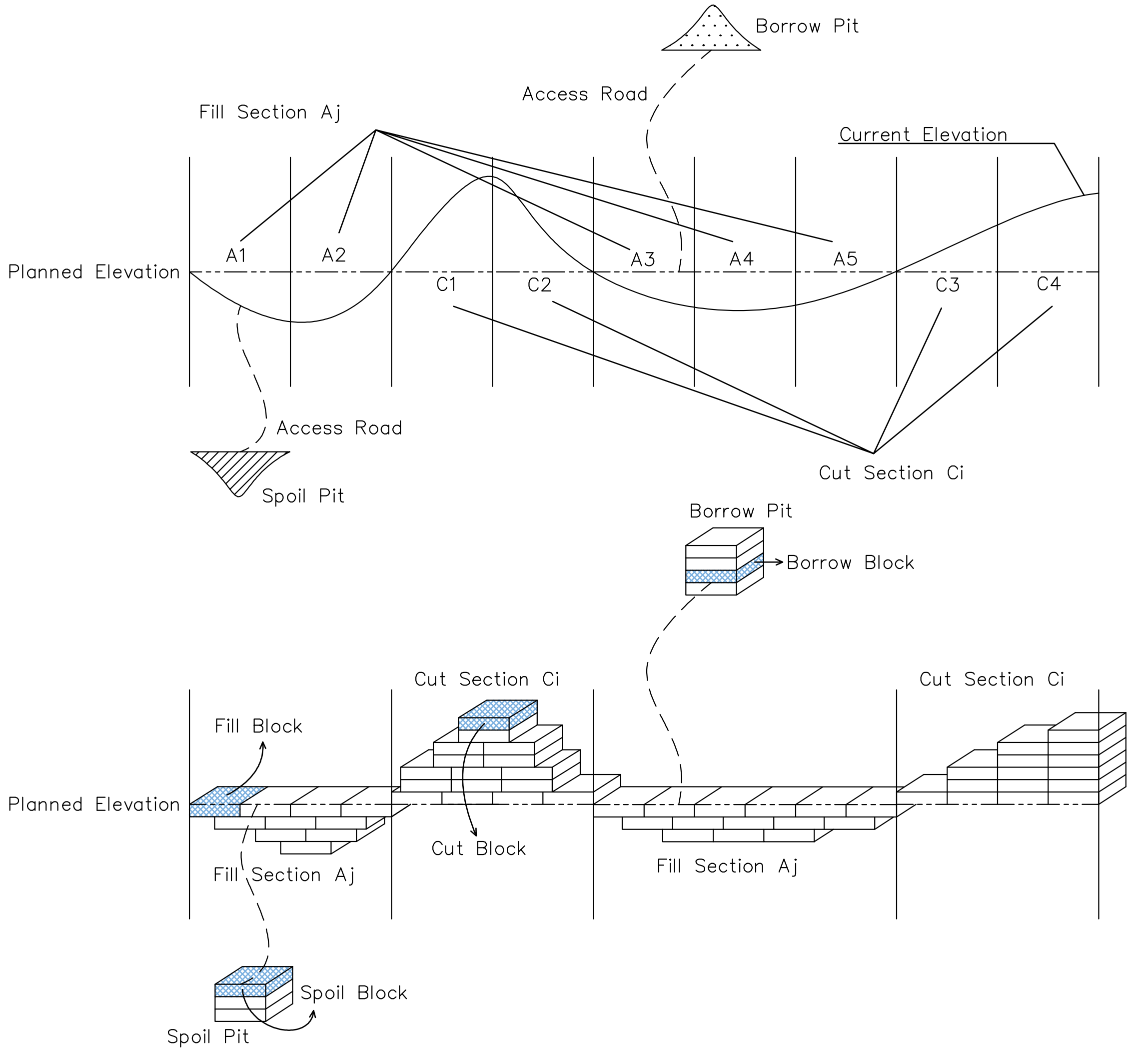
In papers on highway engineering, earth allocation models took the place of graphical methods (e.g., mass diagrams) as management tools. These optimization problems are generally based on the classical transportation problem (ORDEN, 1956), where the sources are represented by cut sections and borrow pits, and the demand areas are represented by fill sections and spoil pits. Additionally, to reduce the haul distances, in most models the cut and fill sections are divided into small areas using regularly spaced road segments (MAYER; STARK, 1981; EASA, 1987; EASA, 1988; JAYAWARDANE; HARRIS, 1990; JAYAWARDANE; PRICE, 1994a; KARIMI *et al.*, 2007; LIMA *et al.*, 2013) or three-dimensional prisms (BURDETT; KOZAN, 2013; BURDETT; KOZAN, 2014; BURDETT *et al.*, 2015; GWAK *et al.*, 2018), as shown in Figure 5.

The analysis of the full texts revealed that most of the studies of nonlinear construction (e.g., buildings, dams, or airports) used optimization approaches related to minimum-cost flow problems (KLEIN, 1967). These studies used a grid-based methodology in which construction sites were divided into small rectangles (MOREB; BAFAIL, 1994) or squares (SON *et al.*, 2005; LI; LU, 2017; LI; LU, 2019). They solved the flow problems using graphs, which are mathematical structures used to model the pairwise relations between two distinct locations. Thus, they used geometric centers as edges where squares or rectangles are cut or filled, and material is transported or received along vertices, as shown in Figure 6.

2.5.2.1.2 Equipment Fleet Planning

Equipment fleet planning problems aim to find the best equipment fleet for a specific situation considering relevant engineering parameters such as the soil/rock type, earthwork volumes, and operational costs. According to Gwak *et al.* (2018), fleet planning models are used to identify the most suitable set of equipment (e.g., loaders, haulers, and compactors) by computing the optimal quantities of each type of equipment and its anticipated productivity.

Figure 5 – Division of earthwork sections into segments



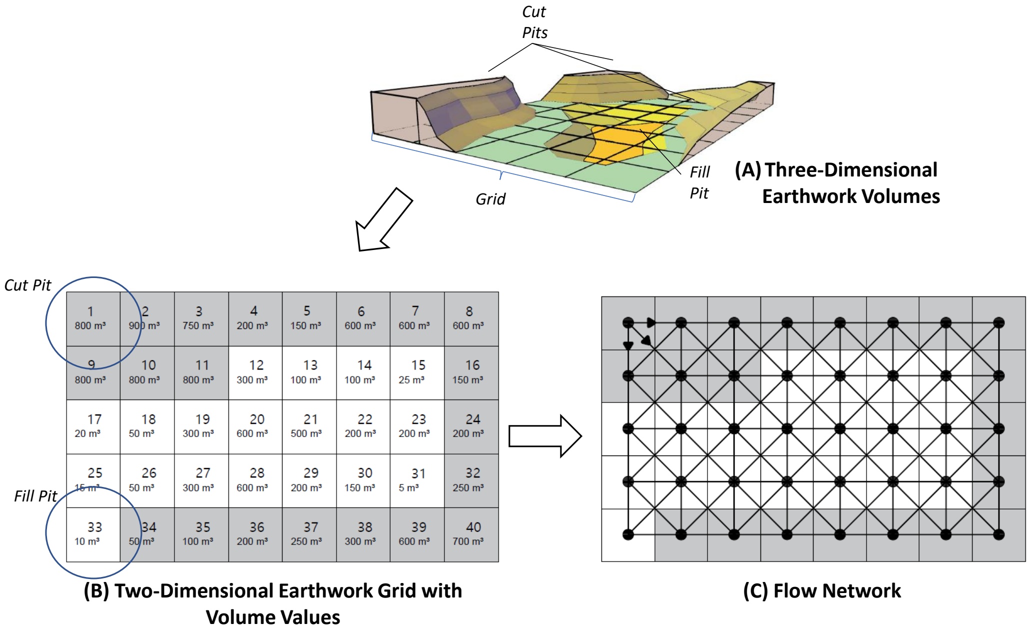
Source: Author

Generally, each piece of equipment corresponds to an integer variable in a configuration vector (Figure 7), and an estimated production value that affects the objective/fitness function for cost and/or time minimization is generated. In contrast to those on other research topics, most studies on fleet planning used both optimization models and simulation tools (MARZOUK; MOSELHI, 2002; MARZOUK; MOSELHI, 2003; MARZOUK; MOSELHI, 2004; ZHANG, 2008; XU *et al.*, 2011; ALSHIBANI; MOSELHI, 2012a; FU *et al.*, 2013), where the productivity indices were obtained by simulation of every proposed configuration for each earthwork scenario.

2.5.2.1.3 Earthmoving Operations Routing

Some papers presented approaches to allocating materials considering equipment routes. I classified problems related to routing into three subproblems: The *Shortest Route Cut and Fill Problem* (SRCFP) (HENDERSON *et al.*, 2003; LIM *et al.*, 2005; SONGSHAN *et al.*,

Figure 6 – Grid-based methodology



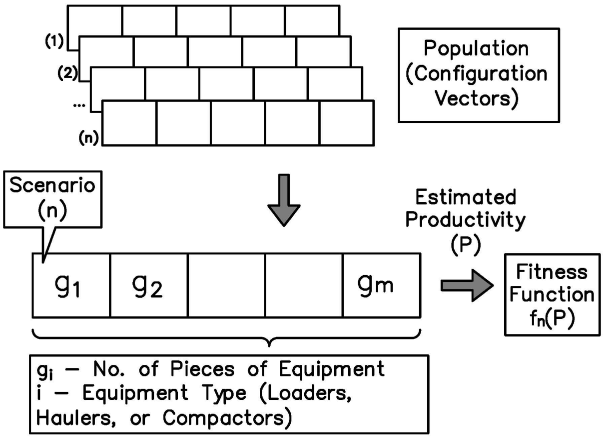
1 800 m^3	2 900 m^3	3 750 m^3	4 200 m^3	5 150 m^3	6 600 m^3	7 600 m^3	8 600 m^3
9 800 m^3	10 800 m^3	11 800 m^3	12 300 m^3	13 100 m^3	14 100 m^3	15 25 m^3	16 150 m^3
17 20 m^3	18 50 m^3	19 300 m^3	20 600 m^3	21 500 m^3	22 200 m^3	23 200 m^3	24 200 m^3
25 15 m^3	26 50 m^3	27 300 m^3	28 600 m^3	29 200 m^3	30 150 m^3	31 5 m^3	32 250 m^3
33 10 m^3	34 50 m^3	35 100 m^3	36 200 m^3	37 250 m^3	38 300 m^3	39 600 m^3	40 700 m^3

(B) Two-Dimensional Earthwork Grid with Volume Values

(C) Flow Network

Source: Author

Figure 7 – Configuration vector



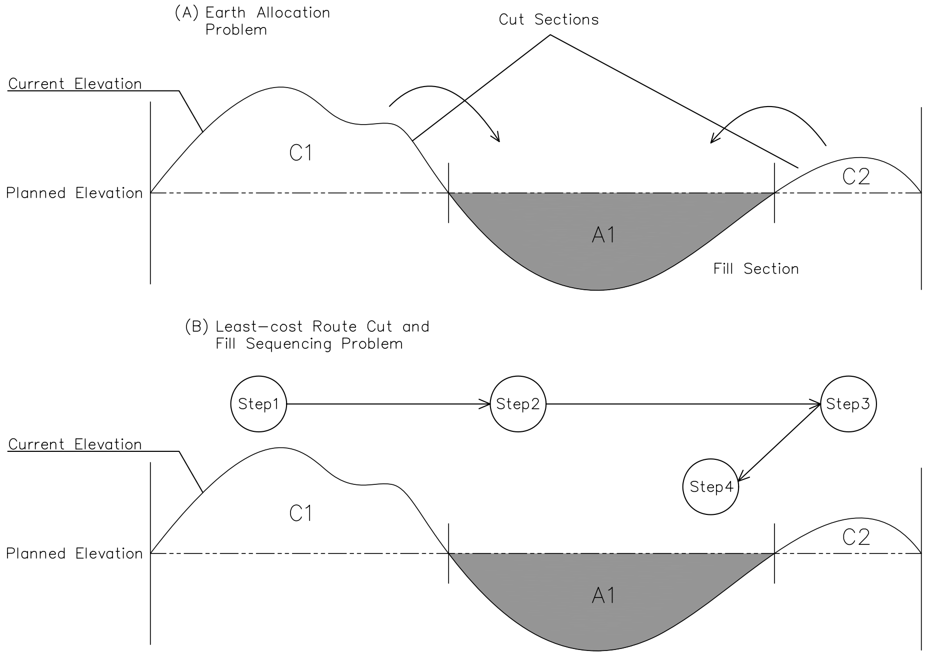
Source: Author

2005), the *Least-cost Route Cut and Fill Sequencing Problem* (LCRCFSP) (NASSAR; HOSNY, 2012), and the *Temporary Road Network Design Problem* (TRNDP) (TAM *et al.*, 2007; LIU *et al.*, 2013; LI *et al.*, 2015; LIU; LU, 2015; YI; LU, 2016; GWAK *et al.*, 2016; YI; LU, 2019).

The SRCFP is an optimization problem for construction site land leveling; its objective is to find an optimal route that minimizes the total distance hauled by a single piece of earthmoving equipment with a unit capacity. According to Henderson *et al.* (2003), the SRCFP is a special case of the *Symmetric Traveling Salesman Problem* (STSP) (GRÖTSCHEL; PADBERG, 1978) because it seeks to find the shortest Hamiltonian cycle. The Hamiltonian cycle in the SRCFP is based on a finite graph formed by alternating cut and fill locations. Therefore, SRCFP-based models limit haulers to travel only from source (cut) to demand (fill), visiting each location exactly once and returning to the initial start point.

In contrast to the SRCFP, the LCRCFSP is not limited to one visit per location and there are not requirements to alternate cut and fill visits. Therefore, the LCRCFSP resembles the earth allocation problem, consedering the volume balance between cut and fill sections. However, it incorporates a sequence of equipment movements in a group of steps and ensures that only one movement between locations is made per step. Consequently, the LCRCFSP allocates earthwork volumes while drawing the least-cost route, as shown in Figure 8.

Figure 8 – Least-cost route cut and fill sequencing problem



Source: Author

I classified problems that draw routes for the selection or construction of temporary roads as TRNDPs. Some TRNDPs aim to find the most economical route for equipment traffic using path-finding algorithms (TAM *et al.*, 2007; GWAK *et al.*, 2016). However, other approaches seek to design an entire temporary haul road network considering the cost and time parameters of earth allocation (LIU *et al.*, 2013; LIU; LU, 2015; LI *et al.*, 2015; YI; LU, 2016; YI; LU, 2019). Additionally, some studies also evaluated the type of surface on the selected routes (e.g., rough ground or a gravel surface), which directly affects the rolling resistance, equipment speed, and time required for haul operations (LIU *et al.*, 2013; LIU; LU, 2015; GWAK *et al.*, 2016; YI; LU, 2016).

2.5.2.1.4 Earthmoving Operations Scheduling

Only four papers (UGWU; TAH, 2002; HSIAO *et al.*, 2011; LIN *et al.*, 2012; HWANG *et al.*, 2014) presented scheduling approaches that targeted the details of earthmoving operations. Similar to equipment fleet planning problems, this scheduling approach models the estimated productivity and uses optimization techniques to find the optimal scheduling configuration considering constraints related to available resources (e.g., trucks, dozers, or excavators). For example, Hsiao *et al.* (2011), Lin *et al.* (2012), and Hwang *et al.* (2014) used simulation approaches to generate schedules and optimization techniques to set the operation order and relationships (concomitant, predecessor, or successor activity).

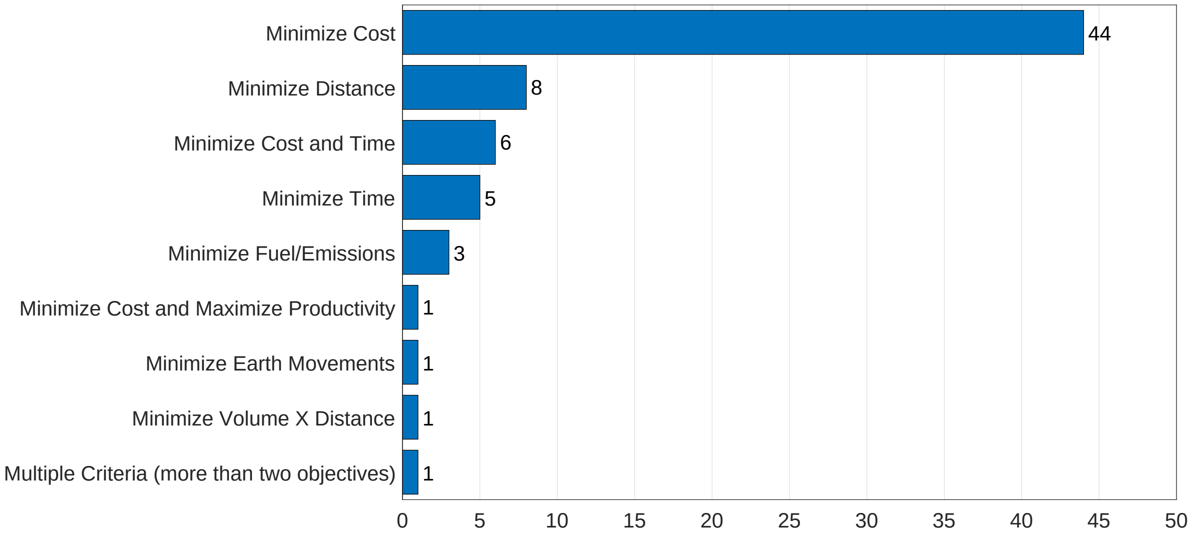
2.5.2.2 Research Question RQ2: What are the research goals of employing optimization techniques in earthmoving planning and operation?

All the selected papers proposed or recommended the use of optimization techniques as management tools to improve one or more aspect of construction. Consequently, the proposed models or algorithms sought to find optimal or near-optimal solutions by maximizing or minimizing key parameters of the analyzed problems such as the distance, cost, time, fuel consumption, and greenhouse gas emissions. Therefore, this mapping study analyzed the objectives of each proposed optimization approach (70 in total); the results are shown in Figure 9.

Figure 9 shows that approximately 63% of the analyzed studies proposed models or algorithms related to cost minimization. There are eight papers with multicriteria objectives, six papers on cost and time minimization, and only two papers with distinct multi-objective approaches: the studies of Pantouvakis and Manoliadis (2008) and Fu *et al.* (2013). Pantouvakis and Manoliadis (2008) presented a compromise programming model for the selection of borrow pits, considering four main criteria related to ecology, human health, geoscience, and engineering. By contrast, Fu *et al.* (2013) proposed a genetic algorithm for fleet selection including two objectives: the minimization of the total cost of ownership (purchasing cost, residual value, depreciation, interest, insurance, taxes, and operational costs) and the maximization of fleet productivity.

Few studies have considered fuel consumption or greenhouse gas emission minimiza-

Figure 9 – Optimization objectives



Source: Author

tion as optimization objectives (BURDETT; KOZAN, 2013; BURDETT *et al.*, 2015; KRANTZ *et al.*, 2017). Burdett and Kozan (2013) and Burdett *et al.* (2015) estimated the fuel consumption by multiplying the consumption rate by the number of hauls required to transport a specific volume of soil. Additionally, Burdett *et al.* (2015) also considered an emission coefficient that estimates the greenhouse gas emissions per liter of fuel consumed. By contrast, Krantz *et al.* (2017) estimated the energy use in an optimized earth allocation and in other road construction activities (e.g., aggregate production). They developed a calculation model to transform the energy consumed in each activity to carbon dioxide emissions.

This mapping study also found very specific objectives for earth allocation models such as those of Son *et al.* (2005) and Ji *et al.* (2010). Son *et al.* (2005) optimized earth allocation using the product of volume and distance ($m^3.m$) as the decision variable in the objective function. In another context, Ji *et al.* (2010) developed a model to divide the road construction site after optimizing the earth allocation, assuming that two or more non-cooperating companies will simultaneously work on each segment. The proposed model minimized the earth movements between segments to avoid shared work between the non-cooperating players.

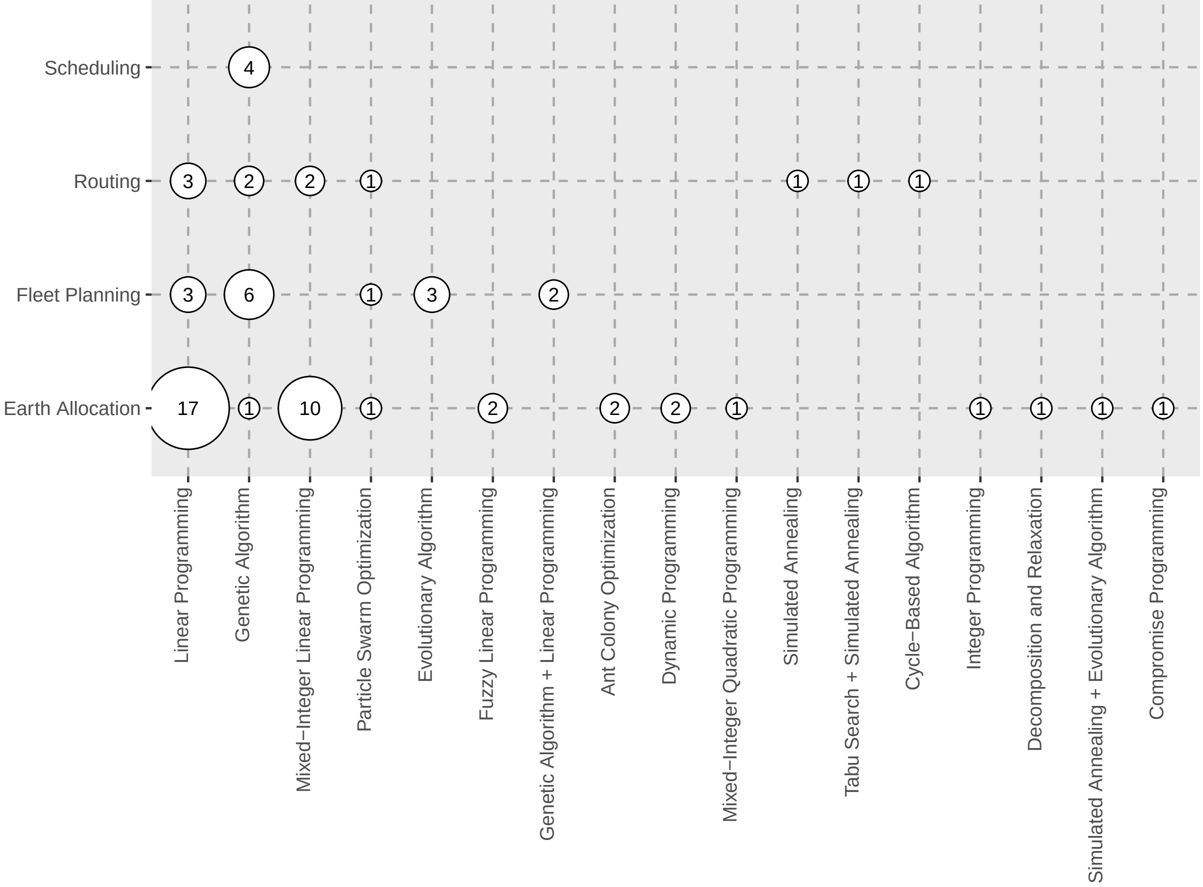
2.5.2.3 *Research Question RQ3: What optimization techniques are used to solve earthmoving optimization problems?*

The optimization problems were solved by 17 distinct optimization techniques, including optimization models (e.g., LP, *Mixed-integer Linear Programming* (MILP), and dynamic programming) and metaheuristic algorithms (e.g., genetic algorithms, tabu search, and simulated annealing). Metaheuristics are generally used for computationally expensive optimization problems that require significant quantities of resources such as time, processing capacity, and memory. Consequently, these algorithms create strategies for finding near-optimal solutions by randomly exploring a wide search space in a reasonable computation time.

I observed that among the optimization solutions, the most commonly used technique was LP (23/70 = 33%), followed by genetic algorithms (13/70 = 19%), and MILP (12/70 = 17%). Furthermore, three papers considered hybrid approaches, merging genetic algorithms and LP (MOSELHI; ALSHIBANI, 2009; ALSHIBANI; MOSELHI, 2012b), tabu search and simulated annealing algorithms (LIM *et al.*, 2005), and simulated annealing and evolutionary algorithms (BURDETT; KOZAN, 2014).

I also analyzed the relationship between the research topics and optimization approaches and the relationship between the optimization objectives and optimization approaches, as shown in Figures 10 and 11.

Figure 10 – Relationships between research topics and optimization techniques



Source: Author

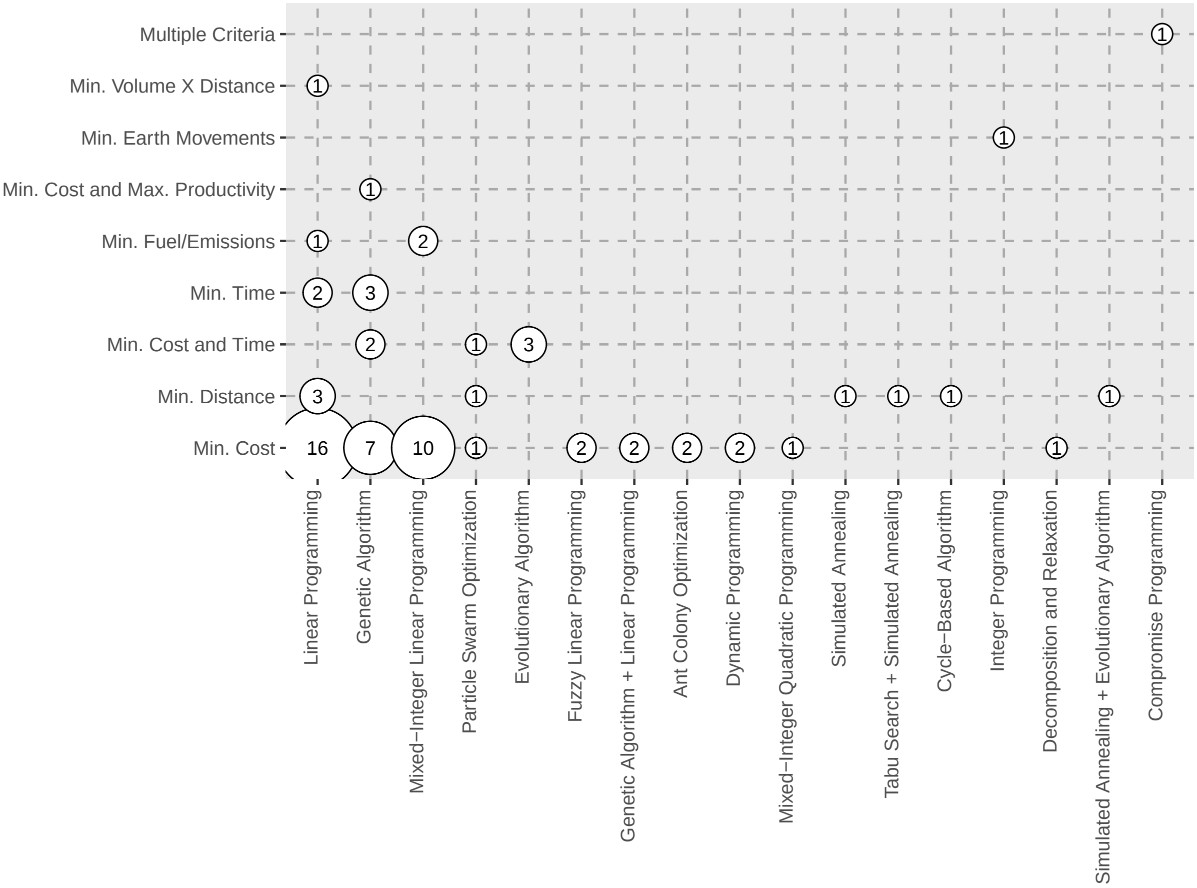
Figure 10 shows that the most commonly explored problem is earth allocation, which is generally solved by LP and MILP models based on the LP formulation of the transportation problem. I also observed that few metaheuristic algorithms were used in earth allocation problems; two studies applied an ant colony optimization approach (KATARIA *et al.*, 2005; MIAO *et al.*, 2011), and just one study used genetic algorithms (AL-TABTABAI; ALEX, 1999). In contrast to those of other research topics, models of earth allocation used fuzzy linear programming to accommodate uncertainty in a parameter, such as the capacity of borrow pits and disposal sites (KARIMI *et al.*, 2007) or the effective demand volume in a rockfill dam (LIU *et al.*, 2012).

Equipment fleet planning problems were solved primarily by genetic algorithms or other types of evolution-based algorithms. The reason is that equipment configuration vectors can be easily represented by chromosomes having a fitness function associated with parameters related to productivity. A significant number of studies also used LP. LP approaches are generally used to select specific equipment that has the minimum unit cost according to constraints related to the maximum loaded weight and available rim pull (JRADE *et al.*, 2012; AZIZ; ABUOL-MAGD, 2015). However, some studies integrated LP as an intermediate stage for fleet selection, first estimating the project total cost by LP and then evaluating fleet combinations using construction site conditions (ALSHIBANI; MOSELHI, 2012a) or genetic algorithms (MOSELHI; ALSHIBANI, 2009; ALSHIBANI; MOSELHI, 2012b).

Routing problems were solved using a relatively wide range of optimization techniques, including LP, MILP, and genetic algorithms for solving TRNDPs, and various metaheuristics such as particle swarm optimization, simulated annealing, and tabu search for solving SRCFPs and LCRCFSPs. By contrast, all scheduling problems were solved by genetic algorithms using specific chromosome structures. For instance, Hsiao *et al.* (2011) and Lin *et al.* (2012) generated chromosomes related to the truck dispatch sequence, whereas Ugwu and Tah (2002) set the cost and duration of each resource allocation as parameters in their chromosome structure.

Figure 11 shows that the most commonly applied optimization techniques (LP, MILP, and genetic algorithms) were used for cost minimization. I also observed that evolution-based approaches were used to solve multiobjective problems, where most studies used the Pareto optimality as the evaluation criterion. For example, Marzouk and Moselhi (2004), Parente *et al.* (2015), and Parente *et al.* (2016) analyzed the evolution of the project duration and cost, choosing an optimal value with the help of a Pareto vector.

Figure 11 – Relationships between objectives and optimization techniques. Min.: minimize. Max.: maximize



Source: Author

2.5.2.4 Research Question RQ4: What types of research have been conducted?

Following the definitions of Wieringa *et al.* (2005) and Petersen *et al.* (2008), I classified the selected papers by research type, where 59 (81.9%) were classified as solution proposals, 9 (12.5%) were experience papers, 1 (1.4%) was evaluation research, and 1 (1.4%) was validation research. Although this mapping study is not a systematic analysis of literature reviews (tertiary studies), 2 literature reviews (2.8%) were included to expand the scope of this study and complement the analysis of earthmoving optimization research.

The classification results show that solution proposals are the predominant research type. Therefore, studies that investigate or analyze the benefits and limitations of the proposed solutions are lacking. Additionally, none of the 9 selected experience studies investigated how engineering companies and government institutions usually develop earthwork projects. Most of the experience papers described how a solution was proposed for a specific complex project.

2.5.2.5 Research Question RQ5: What is the target audience of this research?

I found that the 72 selected papers had three target audiences: academia (35/72 = 48.6%), industry (9/72 = 12.5%), and both academia and industry (28/72 = 38.9%). The studies that targeted academia proposed or evaluated optimization approaches in the context of modeling and performance using fictional numerical examples. By contrast, those that targeted industry were typically case studies that developed models and algorithms for a specific industrial problem. Some of these studies were written by civil and industrial engineering practitioners as well as professors and researchers (CAO *et al.*, 2006; TIAN *et al.*, 2012; BOGENBERGER *et al.*, 2015; DELL'AMICO *et al.*, 2016).

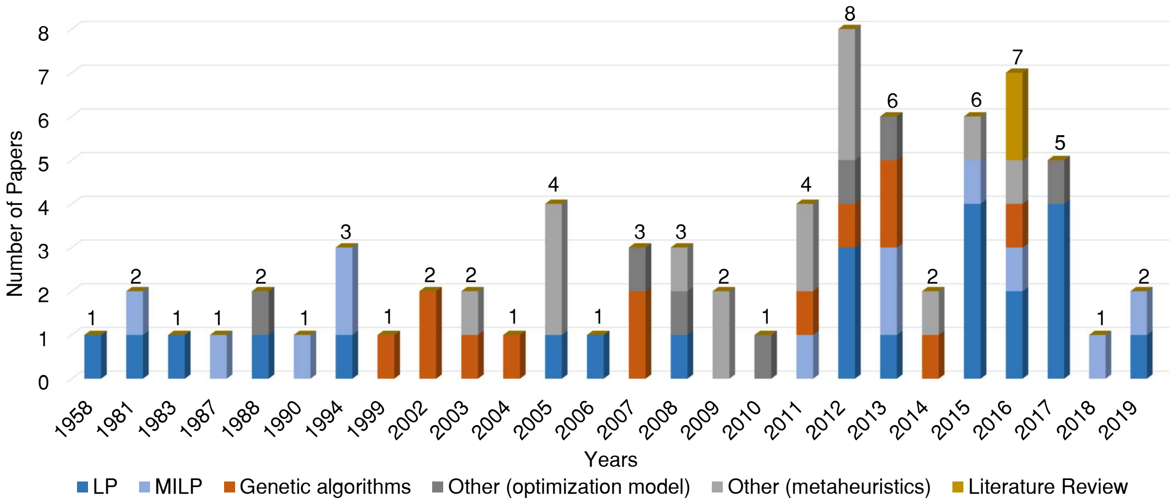
The studies that simultaneously targeted academia and industry proposed and analyzed optimization solutions that included important engineering considerations (e.g., soil type, equipment characteristics, or excavation order). Consequently, these studies used real-world data to validate the proposed models or algorithms, showing that the suggested approaches can be used in real earthwork projects. For example, Lima *et al.* (2013) proposed an MILP model of earth allocation that included soil and aggregate mixing in pavement layers and validated it with data from three highway projects.

I also mapped the type of construction presented and analyzed in each selected paper. I found that 38 papers (52.8%) discussed general applications, which did not limit the research to one type of construction. By contrast, 23 papers (31.9%) presented optimization solutions for road construction, and 7 papers (9.7%) reported solutions for the construction of hydraulic systems, including dams and hydropower plants. Some exceptions were found, such as papers covering the construction of defense facilities (NANDGAONKAR, 1981) and airports (PERRY; ILIFF, 1983). Furthermore, the selected literature did not focus on a specific type of earthwork construction; thus, it was classified as *not applicable*, as described in Appendix A.

2.5.2.6 Research Question RQ6: When and where were the studies published?

In Figure 12, I present the temporal distribution of the selected papers. I found that most papers were published in the 2010s, with two peaks in 2012 and 2016. This relative growth can be partially explained by the introduction of other types of metaheuristics in addition to genetic algorithms, which were first introduced for earthworks in the late 1990s. Additionally, a significant number of LP and MILP approaches were proposed in the 2010s, most of which were related to innovations in earth allocation problems.

Figure 12 – Number of studies per year according to method



Source: Author

To answer the second part of this research question (where were the selected studies published?), I looked at the journals and proceedings in which the articles appeared. I found that most of the selected studies were published in academic journals (58/72 = 80.6%), whereas only 12 were published in conference proceedings (12/72 = 19.4%). Furthermore, the predominant amount of papers were published in civil engineering or operations research journals as shown in Table 7.

I also analyzed which countries had significant representation among the selected papers. Canada contributed by far the largest percentage of papers (19/72 = 26.4%), followed by mainland China (11/72 = 15.3%), South Korea (11/72 = 6.9%), and Australia (11/72 = 5.6%), as shown in Figure 13. Canada also had the most authors who were frequently involved in the selected studies, including the top three researchers with large numbers of publications, as shown in Table 8.

2.5.2.7 *Research Question RQ7: What were the main outcomes of using optimization techniques in earthmoving?*

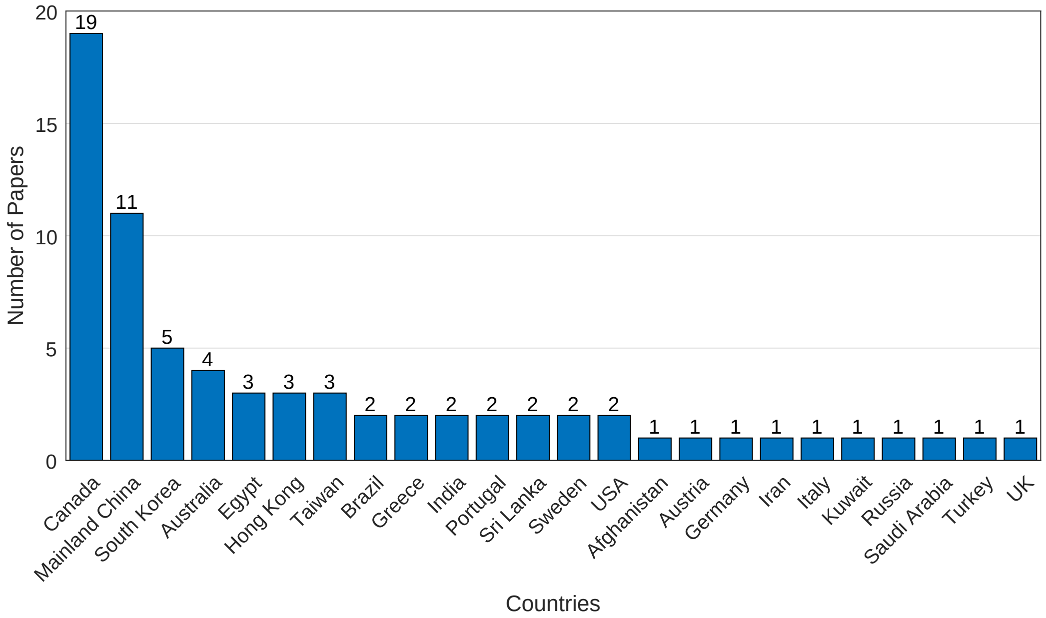
The analysis of the full texts revealed that most (59/72 = 81.9%) of the selected papers reported the cost and total distance savings as the main research contributions. In some cases, the optimal solution was compared to the original budget or hauling plan. For instance, Nandgaonkar (1981) obtained a total distance reduction of 3% for soil transportation and 4.7%

Table 7 – Most frequent journals/proceedings

Journal/Proceedings	Number of papers
Journal of Construction Engineering and Management	12
Canadian Journal of Civil Engineering	4
Journal of the Operational Research Society	3
Construction Management and Economics	3
European Journal of Operational Research	3
Automation in Construction	3
Applied Mechanics and Materials	3
Journal of the Construction Division	2
Proceedings of the Institution of Civil Engineers: Transport	2
Engineering, Construction and Architectural Management	2
Journal of Computing in Civil Engineering	2

Source: Author

Figure 13 – Distribution of studies by country



Source: Author

for rock transportation. Perry and Iliff (1983) reduced the total distance by 12.2%, whereas Lima *et al.* (2013) realized cost savings of 3.47% and 3.92% compared to the original budgets of two highway projects.

Although many authors presented reduction in the distances and costs as the main study contributions, none of the selected studies presented an analysis of the impact of the optimized allocations, routes, and schedules after the planning and pre-construction stages. Thus, there is a lack of research that evaluates the usage of the optimized plans in daily construction, which involves several uncertainties. As an illustration, in allocation problems, the excavated soil can present an inferior bearing capacity compared to the previous geotechnical investigations, being unsuitable for a certain earthmoving layer. Other common example is related to equipment fleet optimization where the estimated production rates generally do not consider construction

Table 8 – Authors most frequently involved in the selected studies

Authors	Number of papers	Institution	Country
Lu, M.	7	University of Alberta	Canada
Moselhi, O.	7	Concordia University	Canada
Alshibani, A.	4	Concordia University	Canada
Burdett, R.L.	3	Queensland University of Technology	Australia
Jayawardane, A.K.W.	3	University of Moratuwa	Sri Lanka
Kozan, E.	3	Queensland University of Technology	Australia
Li, D.	3	University of Alberta	Canada
Liu, C.	3	University of Alberta	Canada
Marzouk, M.	3	Cairo University	Egypt
Cheng, T.	2	Chaoyang University	Taiwan
Correia, A.G.	2	University of Minho	Portugal
Cortez, P.	2	University of Minho	Portugal
Dell'Amico, M.	2	University of Modena and Reggio Emilia	Italy
Easa, S.M.	2	Lakehead University	Canada
Fuellerer, G.	2	STRABAG AG	Austria
Hosny, O.	2	The American University in Cairo	Egypt
Hsiao, W.	2	Chaoyang University of Technology	Taiwan
Iori, M.	2	University of Modena and Reggio Emilia	Italy
Lee, D.	2	KyungPook National University	South Korea
Lim, A.	2	The Hong Kong University of Science and Technology	Hong Kong
Lin, C.	2	National Chung Hsing University	Taiwan
Nobre Júnior, E.F.	2	Federal University of Ceará	Brazil
Novellani, S.	2	University of Modena and Reggio Emilia	Italy
Parente, M.	2	University of Minho	Portugal
Prata, B.A.	2	Federal University of Ceará	Brazil
Price, A.D.F.	2	Loughborough University	UK
Son, J.	2	Hongik University	South Korea
Yi, C.	2	University of Alberta	Canada

Source: Author

delays, operator's inexperience or indolence.

When it comes to environmental planning, most studies presented optimization objectives only based on construction costs, ignoring aspects related to both air and noise pollution. However, these approaches can indirectly benefit the environment. According to Parente *et al.* (2015), optimization solutions for resource allocation improve the efficiency of equipment use. Consequently, the environmental impacts are reduced because less fuel is consumed, and the greenhouse gas emission to the atmosphere is reduced.

In addition to the outcomes related to cost-efficiency and the environment, many studies made significant contributions to problem modeling and improved the models/algorithms to comply with engineering requirements. In the context of earth allocation problems, many papers introduced constraints related to the project conditions in light of the borrow and disposal pit characteristics (MAYER; STARK, 1981; EASA, 1987; EASA, 1988; AL-TABTABAI; ALEX, 1999; KATARIA *et al.*, 2005; KARIMI *et al.*, 2007), obstacles in equipment paths (e.g., rivers, vegetation, or topographical features) (HARE *et al.*, 2011), and novel techniques for segmentation of cut and fill areas (BURDETT; KOZAN, 2013; BURDETT; KOZAN, 2014; BURDETT *et al.*, 2015; GWAK *et al.*, 2018). In general, most of the solutions could incorporate these new features with satisfactory computational performance, being adaptations of polynomial algorithms, as mentioned in Section 2.5.2.1.1.

However, especially in highway construction, few allocations studies brought the vision of specialized professionals intending to improve the model's applicability in real construction planning. Among the exceptions, two studies stand out in the field. First, the study of Lima *et al.* (2013) incorporated the extensive experience of a senior engineer, developing an optimization methodology as closely as possible to its application in real-world projects. In more detail, Lima *et al.* (2013) expanded the earth allocation model of Mayer and Stark (1981) to paving operations, working with material mixing and different soil strata. The next example comes from the study of Bogenberger *et al.* (2015) that developed an optimization model to improve real-world activities performed by a construction company. In brief, Bogenberger *et al.* (2015) introduced a two-phase optimization system based on linear programming that includes the allocation flow of several material types (e.g., soil, concrete, and asphalt) and material recycling. In the first phase, the model determines the overall project feasibility, whereas, in the second phase, the model determines the optimized flow of each material.

In contrast to earth allocation problems, fleet planning and scheduling problems contributed to developing efficient integrated systems. For example, 86.7% (13/15) of the fleet planning problems and 75% (3/4) of the scheduling problems required some auxiliary computational technique. As mentioned in Section 2.5.2.1.4, many studies used simulations, but some also incorporated techniques such as GIS visualization (ALSHIBANI; MOSELHI, 2012b; PARENTE *et al.*, 2016), GPS tracking (MOSELHI; ALSHIBANI, 2007a; MOSELHI; ALSHIBANI, 2009; ALSHIBANI; MOSELHI, 2012a), and data mining (PARENTE *et al.*, 2016) into evolutionary algorithms. Generally, geographical information (equipment routes or positioning information) and data analysis techniques are used to estimate productivity, whereas metaheuristic algorithms indicate the best fleet or schedule configuration. Furthermore, three papers (MOSELHI; ALSHIBANI, 2007a; MOSELHI; ALSHIBANI, 2009; ALSHIBANI; MOSELHI, 2012a) also presented solutions consisting of monitoring systems that can constantly observe the productivity. Thus, this integrated system can dynamically recalculate the fleet configuration in case of a productivity decrease, providing timely corrective actions.

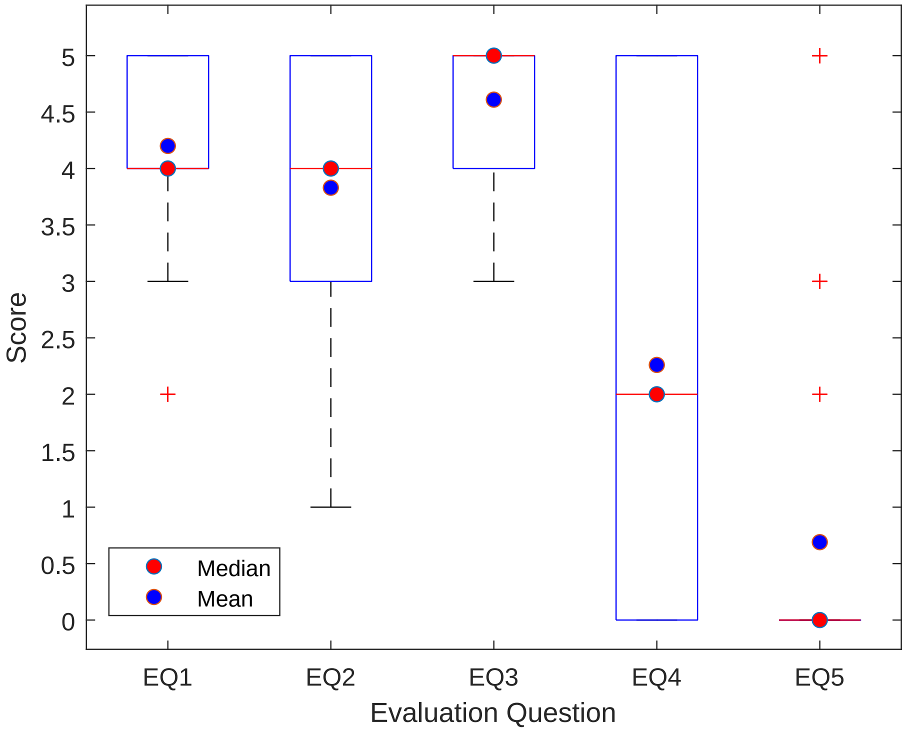
The proposed solutions to routing problems introduced innovative engineering approaches to equipment operation sequencing (HENDERSON *et al.*, 2003; LIM *et al.*, 2005; SONGSHAN *et al.*, 2005; NASSAR; HOSNY, 2012) and the design of haul routes (TAM *et al.*, 2007; GWAK *et al.*, 2016; LIU *et al.*, 2013; LI *et al.*, 2015; LIU; LU, 2015; YI; LU, 2016; YI; LU, 2019). The use of SRCFPs and LCRCFSPs first demonstrated the need to plan equipment sequences and routes when planning earth allocation. According to Nassar and Hosny (2012), the unit costs for hauling operations in earth allocation problems fail to adequately represent the current hauling cost, considering only the distance between each cut and fill section while ignoring the equipment route and operation sequence. Therefore, approaches that consider some type of sequence can provide more accurate hauling cost estimation and avoid excessive returns to sources that have already been excavated. However, this type of model is computationally expensive, limiting studies to find near-optimal solutions through metaheuristic algorithms, as shown in Section 2.5.2.3.

By contrast, the studies using TRNDPs did not focus on operation sequencing, but provided options to construct temporary haul roads. Two main approaches were used. First, genetic algorithms were used to perform an exhaustive search of optimal haul routes considering the start, intermediate, and target points, the job site terrain (e.g., surface condition, grade, and rolling resistances) (GWAK *et al.*, 2016), and obstacles (TAM *et al.*, 2007). Second, some studies (LIU *et al.*, 2013; LI *et al.*, 2015; LIU; LU, 2015; YI; LU, 2016; YI; LU, 2019) considered designing a complete temporary haul road network in which the paths have different rolling surface conditions. These conditions directly affect the earth allocation parameters such as the cost and hauling time between sections. As a consequence, the proposed approaches generate and test network layouts based on these optimum cost/time criteria, using different techniques such as genetic algorithms (LIU *et al.*, 2013), MILP (YI; LU, 2016), or predefined layout options (LIU; LU, 2015).

2.5.3 Quality Assessment Results

I evaluated the primary studies by rating the answer to each evaluation question on a scale of 0 to 5, where 0 means “Not at all” and 5 means “Completely” as mentioned in Section 2.4.5. I obtained a mean value of 4.20 for *EQ1* (Does the study present models or algorithms that can be replicated in real-life earthmoving operations?), 3.83 for *EQ2* (Does the model used in the study include engineering considerations?), 4.61 for *EQ3* (Is the problem successfully represented by a model or algorithm?), 2.26 for *EQ4* (Does the study present evidence of computational performance?), and 0.69 for *EQ5* (Does the study mention any positive effects of optimization in reducing the environmental impacts of earthmoving operations?). I also analyzed the variability of the results, as shown in Figure 14.

Figure 14 – Answers to each evaluation question



Source: Author

EQ1 and *EQ3* had acceptable variability, where most scores were between 4 and 5. Therefore, I inferred that most studies had satisfactory replicability in real-life situations and exhibited adequate performance in modeling earthwork optimization problems. By contrast, *EQ2* exhibited greater variability than *EQ1* and *EQ3*. Consequently, I observed that most evaluations were closer to "Completely"but the evaluations of a considerable number of papers were closer to "Not at all". In other words, some studies did not cover essential engineering considerations. There were two main reasons. First, some older studies from early stages of research adapted mathematical models from other management applications. Therefore, some approaches used a formulation similar to that of the original model, ignoring some technical aspects and focusing on solving the optimization problem. Second, some studies focused on improving the computational performance of existing models and ignored aspects of real-life construction.

EQ4 had a larger variability than any other evaluation question. Consequently, I analyzed the rating results by searching for patterns. I found that most papers that reported LP and MILP approaches (21/35 = 60%) did not present any information on the computational performance. In addition, most of the papers related to metaheuristics (24/28 = 85.6%) presented some type of information on the computational performance, and most (16/28 = 57.1%) had scores between 3 and 5. Therefore, I attributed these sparse results to the fact that most LP and MILP models had polynomial-time solutions. Consequently, many models did not represent the performance in detail, whereas the feasibility of the proposed metaheuristics compared to solvers or other algorithms had to be demonstrated.

In contrast to *EQ4*, *EQ5* received consistent scores overall with some outliers. Most papers did not discuss or even suggest the positive effects of optimization in reducing environmental impacts. Consequently, I observed that the neglect of environmental effects of earthwork optimization is the most common gap in the research field. However, some exceptions were noted in the last decade. For example, Burdett and Kozan (BURDETT; KOZAN, 2013; BURDETT; KOZAN, 2014), Burdett *et al.* (2015), and Krantz *et al.* (2017) presented approaches that reduce fuel and energy consumption, and Chu *et al.* (2012), Bogenberger *et al.* (2015), and Dell'Amico *et al.* (2016) included resource recycling in their models.

2.6 Conclusions

I presented a mapping study of research on optimization in earthmoving planning and operation in which I analyzed the literature in terms of the problem characteristics, research objectives, and optimization techniques.

First, I observed that the earliest papers (KANTOROVITCH, 1958; MAYER; STARK, 1981; NANDGAONKAR, 1981; PERRY; ILIFF, 1983; EASA, 1987; EASA, 1988; CHRISTIAN; CALDERA, 1988; JAYAWARDANE; HARRIS, 1990; JAYAWARDANE; PRICE, 1994a; JAYAWARDANE; PRICE, 1994b; MOREB; BAFAIL, 1994) focused on earthwork allocation planning problems, thus minimizing the overall distance between cut and fill areas or minimizing the total cost associated with excavation, hauling, and compaction. Subsequently, I found that an increasing number of researchers started to present other optimization problems related to earthmoving operations and proposed solutions to equipment fleet allocation, scheduling, and routing problems. For example, Al-Tabtabai and Alex (1999) introduced a genetic algorithm for allocating labor and equipment, which was followed by the studies of Marzouk and Moselhi (MARZOUK; MOSELHI, 2002; MARZOUK; MOSELHI, 2003; MARZOUK; MOSELHI, 2004), whereas Henderson *et al.* (2003) proposed a simulated annealing algorithm for earthmoving routing, which was improved by Lim *et al.* (2005) and Songshan *et al.* (2005).

I also concluded that recent studies, in contrast to previous research, focused on improving well-known mathematical models rather than presenting new problems. Consequently, most studies in the last 10 years have introduced constraints related to construction characteristics in existing allocation models. For instance, Hare *et al.* (2011) included constraints to an MILP model to limit earth movements blocked by natural obstacles. Another recent example is the study of Gwak *et al.* (2018) which added constraints to the excavation and filling order to a problem in which cut segments were excavated in a top-down sequence, while fill segments were backfilled in a bottom-up sequence.

After mapping all the optimization techniques, I observed patterns in the relationship between optimization techniques and earthwork optimization problems. I realized that LP or MILP approaches are generally used for earth allocation because these problems are usually based on classical LP approaches, such as the transportation problem (ORDEN, 1956) and minimum-cost flow problem (KLEIN, 1967), which are not computationally expensive. By contrast, the routing problems considered operation sequencing for drawing routes, demanding processing time, and memory to obtain the optimal solutions. Consequently, 50% (5/10) of the routing approaches used metaheuristic algorithms. Most fleet allocation and scheduling studies (15/18 = 83%) used evolution-based metaheuristic algorithms to randomly test the equipment configuration in various scenarios and choosing the best fleet using an effective selection strategy. According to Lin *et al.* (2012), these algorithms are used as filters to screen out infeasible fleets and schedules.

During the full-text analysis, I observed that most journal articles were written as solution proposals. Consequently, I could conclude that there is a lack of analytical studies that aims to integrate past contributions and evaluate possible benefits and limitations of using optimization techniques in earthmoving operations. Furthermore, in Section 2.5.2.7, I also found that none of the selected articles evaluated the impact of using optimization techniques in daily construction, limiting their analysis to planning and pre-construction stages. As a result, future research has the opportunity of looking backward to systematically consolidate and compare past contributions, at the same time it needs to look ahead to evaluate approaches after their development, analyzing how they work in practice with scenarios of uncertainty.

In Section 2.5.2.7, I found that few papers considered the experience of specialized professionals to improve the applicability of the proposed models. Consequently, the exceptions

(LIMA *et al.*, 2013; BOGENBERGER *et al.*, 2015) developed optimization approaches as close as possible to construction reality. Therefore, future research can include practical aspects of construction, expanding their focus into multi-commodity flows related to earthmoving and paving operations where not only the activities of processing, mixing and recycling distinct materials need to be taken into account but also the geotechnical requirements of the destinations (earthmoving and pavement layers) need to be considered. Furthermore, future research can also integrate the construction of haul roads in modeling, detailing the equipment routes to bring more realistic construction costs.

Finally, I drew my conclusions about the quality assessment performed in Section 2.5.3. According to the results, I could confirm that most of the selected papers neglected environmental impacts in their analysis. Consequently, forthcoming studies can build their objectives and constraints to reduce emissions (BURDETT; KOZAN, 2013; BURDETT; KOZAN, 2014; BURDETT *et al.*, 2015; KRANTZ *et al.*, 2017) and make sustainable use of the available resources (CHU *et al.*, 2012; BOGENBERGER *et al.*, 2015; DELL'AMICO *et al.*, 2016). Furthermore, optimization techniques can also be utilized in environmental decision-making, considering multiple optimization objectives related to subjective aspects such as ecology, engineering, and society (PANTOUVAKIS; MANOLIADIS, 2008).

3 OPTIMIZATION OF EARTHMOVING AND PAVING OPERATIONS: ALLOCATION MODEL CONSIDERING MULTIPLE TEMPORARY HAUL ROADS

3.1 Abstract

This paper presents a new approach for optimizing earthmoving and paving operations which takes into account the technicalities of construction site logistics. Unlike in previous studies, I developed a mixed-integer linear programming model for material allocation in road constructions to decide which haul road alternative should be constructed to link material sources to destinations. I also modeled other constraints related to geotechnical conditions; soil and aggregate mixing; and hot-mix asphalt manufacturing. I applied the proposed approach in practice for a 27.84 km long road-construction project in the State of Ceará, Brazil, demonstrating the efficiency of the model in realistic applications.

3.2 Introduction

Earthmoving and paving operations are the most expensive steps in road construction, involving complex processes such as excavation, loading, transportation, filling, and compaction (LIMA *et al.*, 2013). According to Bogenberger *et al.* (2015), an earthmoving operation can be defined as construction works deployed to level the earth's surface, wherein the soil and rocks from areas that have them in excess are excavated and transferred to fill the areas with a soil deficit. Earthmoving is followed by paving, wherein a pavement structure is built through the compaction of superimposed layers above the subgrade, generally including a sub-base layer, a base layer, and a hot mix asphalt (HMA) or concrete surface (PAPAGIANNAKIS; MASAD, 2008).

Both earthmoving and paving require efficient logistical planning because of the complex steps involved, such as soil and rock excavation, production of manufactured materials (e.g.: *Hot Mix Asphalt* (HMA) and concrete), and other specific requirements for layer construction. For this reason, many researchers have used operation research techniques to plan road projects (MAYER; STARK, 1981; NANDGAONKAR, 1981; EASA, 1987; EASA, 1988; JAYAWARDANE; HARRIS, 1990; JAYAWARDANE; PRICE, 1994a; JAYAWARDANE; PRICE, 1994b; HARE *et al.*, 2011; LIMA *et al.*, 2013; BOGENBERGER *et al.*, 2015; CHOUDHARI; TINDWANI, 2017; GÜDEN; SÜRAL, 2017; GWAK *et al.*, 2018). Most of them followed a transportation problem-based approach (ORDEN, 1956). Their proposed models ensure that an optimum allocation is made based on the cost, travel distance, or greenhouse gas emissions minimization when moving soil from the source (e.g., cut sections, borrow pits, and quarries) to an intermediary or final destination (e.g., fill sections, disposal areas, pavement layers, and depots) (BURDETT *et al.*, 2015).

Although the above-mentioned studies incorporate logistics and engineering aspects of road construction, they consider just one route to access the target areas in source-destination allocations, ignoring the fact that material sources can use many other haul roads to access different points of the construction site (main road). To address this, I propose a MILP model to allocate all the materials employed in the earthmoving and paving operations taking into account the cost of construction of one or more temporary haul roads between the external sources (borrow pits, quarries, and plants) and the main road. In addition, I included the cost of placing and installing one or more processing plants in various locations along the road. Validation and analysis were performed by applying the MILP model in the CE-085 road project located in Ceará, Brazil.

3.3 Literature Review

Based on the systematic review presented in Chapter 2, I investigated studies that applied optimization techniques in road construction logistics. I analyzed the evolution of optimization approaches used for material allocation by observing how the paving operations are modeled. Subsequently, I examined studies that developed models for routing, designing, or choosing temporary haul roads, looking for distinct ways to include the construction of these paths in an allocation model.

3.3.1 Earth Allocation Problems and Paving Operations Modeling

Studies that used operations research techniques in road construction prioritized the problems related to earthmoving operations. The first *Linear Programming* (LP) model used in road construction was suggested by Stark and Nicholls (1972) and developed by Mayer and Stark (1981). According to Gwak *et al.* (2018), Mayer and Stark (1981) solved the issues pertaining to earth allocation, by optimizing the allocations between cut and fill sections, minimizing the costs related to excavation, transportation, and compaction. They also suggested the use of borrow pits in case of material shortage and the use of disposal areas when excess material from cut sections needs to be discarded.

Following the approach of Mayer and Stark (1981), several authors adapted their earth allocation model and added other specific engineering features. For example, Easa (1987) and Easa (1988) considered non-constant costs for earth allocations, where both the unit costs were based on volume-dependent functions. They proposed a MILP model that incorporated stepwise unit costs and a *Mixed-integer Quadratic Programming* (MIQP) model that included a linear function for calculating unit costs. Other adaptations were found in the studies of Jayawardane and Harris (1990), Jayawardane and Price (1994a), and Jayawardane and Price (1994b), by adding a time constraint for road construction, according to which the time necessary to complete the project is given by the ratio of the volume of soil moved in m^3 and the equipment productivity in m^3/h. The necessary time must be less than or equal to the proposed project duration in order to meet the project deadline. In addition, constraints related to geotechnical characteristics were considered, ensuring that only the soil that meets the quality requirements of a specific earthmoving layer should be used.

In addition, researchers have introduced novel earth allocation models to solve highly sophisticated problems. To illustrate this, Hare *et al.* (2011) developed an MILP model to solve an allocation problem that included the presence of physical obstacles along the road, excluding the earth allocations blocked by rivers, topographical features, or the flora in the region. Another innovative approach was introduced by Gwak *et al.* (2018), wherein the allocation problem was modelled by considering the excavation sequence. Hence, they divided the cut and fill sections in small three-dimensional pieces, including constraints that guaranteed the excavation of cut section pieces in top-down order and backfilling of fill section pieces in a bottom-up order.

Even though multiple allocation approaches exist, only a handful incorporated paving operations. Exceptions include Lima *et al.* (2013), Bogenberger *et al.* (2015), and Choudhari and Tindwani (2017).

Lima *et al.* (2013) proposed one of the first earthwork allocation models that included paving operations. Boolean variables were used to decide the cheapest way of mixing materials for construction of soil-aggregate sub-base and base layers. The model had to choose between mixing materials in situ and or in manufacturing plants. Bogenberger *et al.* (2015) developed a model based on the minimum cost flow problem (KLEIN, 1967), optimizing the allocation flows of ten materials such as soil, bitumen, aggregates, and cement. Bogenberger *et al.* (2015) also included the process of recycling in modeling using recycled aggregates for the production of

HMA and concrete.

In contrast to Lima *et al.* (2013) and Bogenberger *et al.* (2015), Choudhari and Tindwani (2017) developed an LP model for planning the three logistical phases of road projects: sourcing, processing, and distribution. Their model minimized the costs related to the allocations between quarries and processing plants and between processing plants and consumption areas, including the cost of material storage and processing. They also considered constraints on the maximum supply capacity of raw material, total volume demanded by pavement segments, and volume balance of the material before and after the processing stage. After modeling, they applied the optimization approach in a complex supply chain that involved different types of processed materials, such as wet mix macadam, dense bitumen macadam, and bituminous concrete.

3.3.2 Inclusion of Temporary Haul Roads in Optimization Approaches

Apart from earth allocation models, several studies have proposed optimization techniques in order to sequence and route earthmoving operations. The first model was introduced by Henderson *et al.* (2003), who developed an integer programming approach for solving a specific adaptation of the *Symmetric Traveling Salesman Problem* (STSP). Their adaptation minimizes the total distance traveled by a single earthmoving vehicle between cut and fill locations, wherein each cut or fill area is visited only once. However, this modeling approach does not entirely reflect the reality of road construction, where trucks need to conduct several visits to execute earthworks and superimposed pavement layers. In addition, the model is computationally expensive and requires metaheuristic algorithms to decrease processing times, such as the integrated approach of Lim *et al.* (2005), which used a tabu search and a simulated annealing algorithm, and the study of Songshan *et al.* (2005), which utilized a cycle-based algorithm.

In contrast to Henderson *et al.* (2003), Nassar and Hosny (2012) created a routing approach that did not require alternating cut and fill locations by including a new dimension in modeling: time steps *t*. These steps were created with the objective of sequencing every movement of the material, restricting the model to make only one allocation per step. Consequently, the model would be able to provide the soil allocation routes once all operations are sequenced by the proposed steps. However, the model developed by Nassar and Hosny (2012) also demands the use of metaheuristic algorithms in order to provide almost optimum solutions in reasonable processing times, limiting the approach to a finite number of cut and fill locations. For example, they tested the instances up to 300 locations.

Other studies have focused on creating entire temporary haul road networks (LIU *et al.*, 2013; LIU; LU, 2015; LI *et al.*, 2015; YI; LU, 2016; YI; LU, 2019) to find the best layout for building a primary pavement (gravel-surfaced) for equipment movement, using algorithms to create layout alternatives. In general, they analyze how the proposed layout works during material allocation using optimization models based on the minimum cost flow problem. These studies also utilized a grid-based methodology in their analysis, in which construction sites are divided into small squares, each of which has an associated cut or fill volume. Thus, the proposed models use the division in material allocation, moving material from the source areas to the demand areas. However, these are limited to the layout of the analyzed construction site. For instance, it is difficult to divide linear construction sites (e.g., highways or railways) into two-dimensional pieces once the site layout is generally long in extension and thin in width.

In contrast to the haul road networks-based approaches, some studies have used optimization algorithms to search for an optimum route between a starting point and a target point. For example, in their studies, Tam *et al.* (2007) and Gwak *et al.* (2016) used genetic algorithms to perform an exhaustive search for a path that presents the minimum travel time or construction cost, considering the parameters related to job site conditions (e.g., obstacles, path surface, and existing access roads). Another example is the case study of Kang and Seo (2013) that integrated a GIS-based method with a least-cost path analysis in ArcGIS (ESRI, 2004). They used a spatial analyst tool to produce a least-cost route based on georeferenced data. In addition, they built their costs based on multiple criteria (ground slope, obstacles, land use, bodies of water, and existing roads) using the *Analytical Hierarchy Process* (AHP) (SAATY, 1988).

Although the optimization models developed to design optimum haul roads are important tools for planning earthmoving and paving operations, this type of analysis can be considered exhaustive in some situations. In a context of large road construction projects, the analysis needs to be performed for every material source and selected target points. Thus, the above-mentioned path-finding algorithms would be run multiple times for every material allocation involving cut and fill sections, borrow pits, disposal areas, quarries, refineries, and processing plants, demanding a lot of time and computer memory. Furthermore, the construction areas of haul roads are generally limited by farms, residential areas, or conservation parks. As a result, in some projects, only existing routes can be used for accessing the main road, limiting in-depth analysis such as the approaches of Tam *et al.* (2007), Kang and Seo (2013) and Gwak *et al.* (2016).

3.4 Proposed Approach

As discussed in Section 3.2, this study had two main objectives. First, I propose to create an optimization model for distributing materials in road construction, including both earthmoving and paving operations. Second, I aim to include the construction of haul roads in the model. Therefore, I developed a MILP model that incorporates these two characteristics, fulfilling the following requirements:

- The optimization model must minimize the total cost of both earthmoving and paving operations;
- It must utilize reasonable and standardized unit costs;
- It must consider different types of soil;
- It must include different earthmoving and pavement layers;
- It must provide satisfactory computational performance and avoid algorithms that deliver near-optimum solutions.

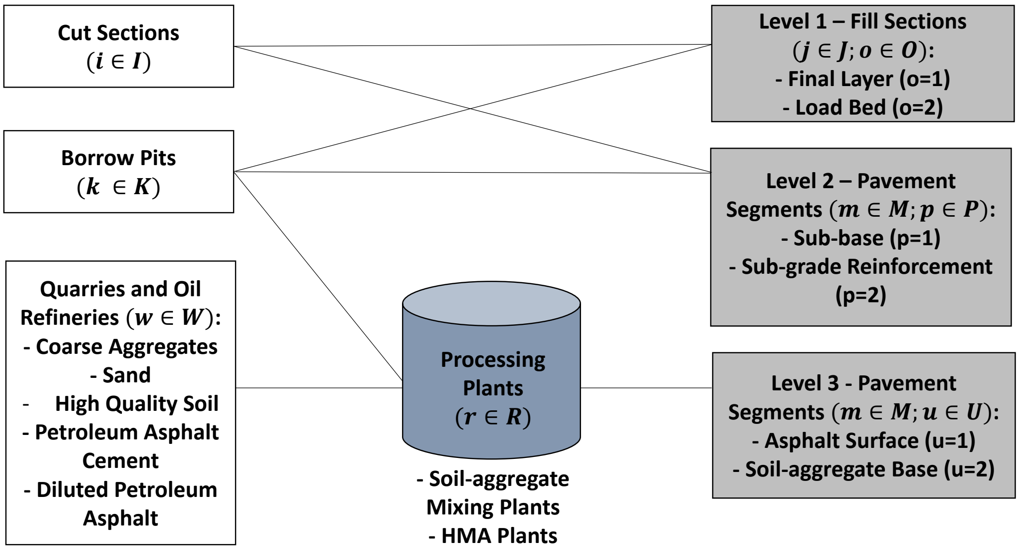
To solve the proposed case study (CE-085 road), I considered Brazilian standards for categorizing materials and layers and calculating the operational costs. In this section, I present how I structured and formulated the mathematical problem considering these engineering features.

3.4.1 Problem Structuring

3.4.1.1 Earthmoving and Paving Operations

I divided the allocations into three distinct levels, as shown in Figure 15. Initially, I set the first level that corresponds to earthmoving allocations where the material from cut sections ($i \in I$) and borrow pits ($k \in K$) are used to backfill the earthmoving layers ($o \in O$) of fill sections ($j \in J$). Next, I set the second level that corresponds to the allocations from cut sections or borrow pits to pavement segments ($m \in M$) in order to build the pavement layers ($p \in P$) composed of raw material. Finally, I set the third level where materials from quarries or oil refineries ($w \in W$) are transported to plants (located in $r \in R$) with the objective of producing soil-aggregate mix and HMA. After processing, these manufactured materials are transported from plants to pavement segments for construction of the base layer and asphalt surface ($u \in U$).

Figure 15 – Earthmoving and paving allocations



Source: Author

For CE-085 road, I considered two distinct earthmoving layers according to the Brazilian standard DNIT 108/2009-ES (DNIT, 2009b), which presents specific requirements for the final layer and the bottom layer called the load bed, as shown in Table 9. In paving operations, I followed the original pavement project that designed a structure with three main layers: a soil sub-base, a soil-aggregate base, and an HMA surface. In some segments, a soil reinforcement layer was added above the subgrade to ensure the required bearing capacity. Furthermore, I followed the requirements of the Brazilian standard DNIT IPR-719/2006 (DNIT, 2006) to select a suitable material for each pavement layer (Table 9).

Table 9 – Quality requirements of earthmoving and pavement layers

Layers	California bearing ratio (CBR)	Expansion (%)	Liquid limit (LL)	Plasticity index (PI)	Group index (GI)
Base	CBR $\geq$ 80%	Exp. $\leq$ 0.5%	LL $\leq$ 25%	PI $\leq$ 6%	-
Sub-base	CBR $\geq$ 20%	Exp. $\leq$ 1.0%	-	-	GI = 0%
Sub-grade reinforcement	Greater than earthmoving final layer CBR	Exp. $\leq$ 1.0%	-	-	-
Final layer	CBR $\geq$ 6%	Exp. $\leq$ 2.0%	-	-	-
Load bed	CBR $\geq$ 2%	Exp. $\leq$ 4.0%	-	-	-

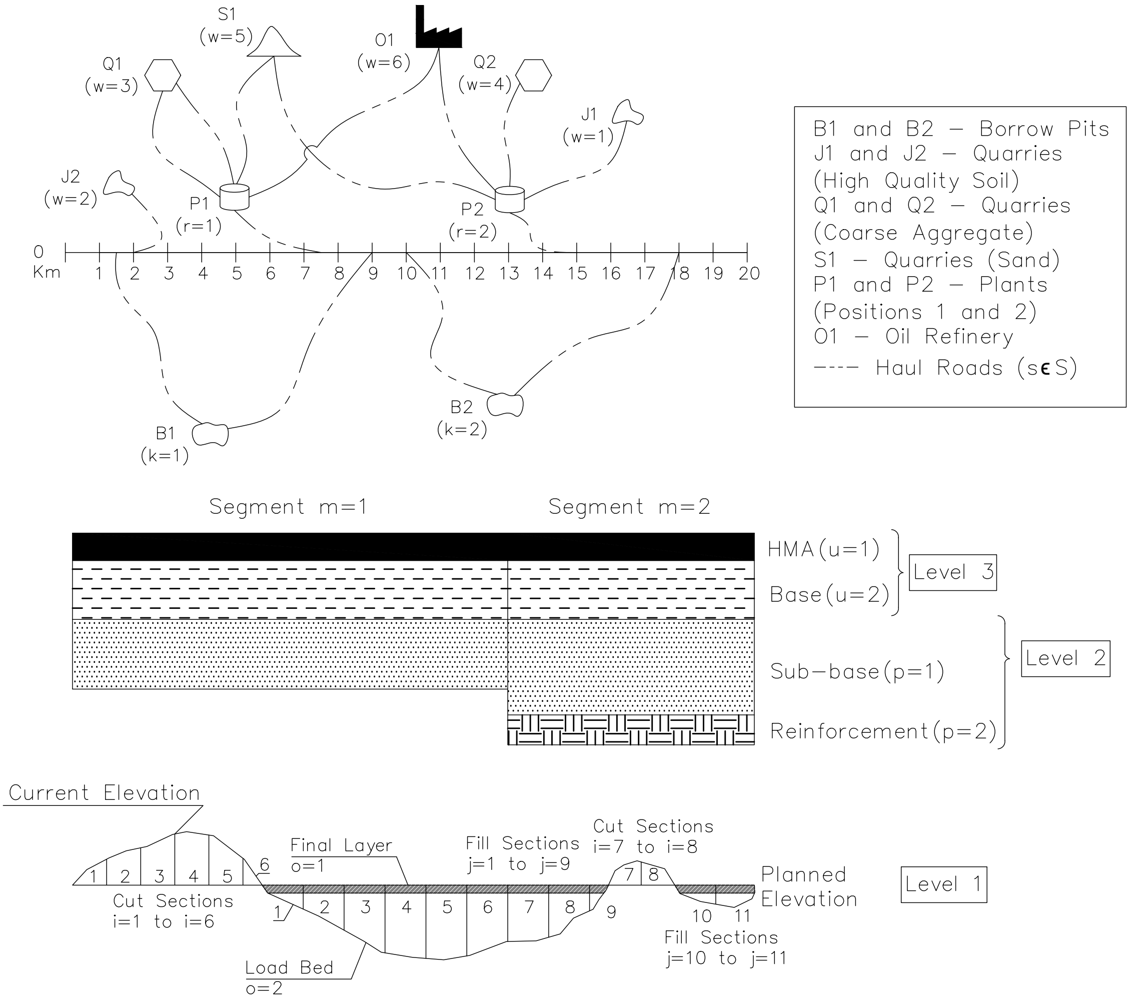
Source: Author

Following the recommendations of environmental studies of CE-085 (DER-CE, 2012), I also utilized the excavated borrow pits as disposal areas where the trenches left after excavation were filled with discarded material from cut sections during the execution of earthmoving operations.

3.4.1.2 *Construction of Haul Roads*

Our model does not choose a unique option between possible routes. It systemically analyzes the construction of haul roads ($s \in S$) considering its impact on earthmoving and paving allocation costs. As an example, borrow pit $B1$ shown in Figure 16 has two access routes targeting the main road. Thus, if the model indicates that the two haul roads have to be built, the model certainly evaluated that the savings in allocations are higher than the cost of building these two segments.

Figure 16 – Schematic of example of road construction logistics



Source: Author

In Figure 16, it can also be observed that the main road is not the only targeted area, and it is an important communication path between source and demand. For example, $Q1$, $S1$, and $O1$ have direct routes to plant position $P1$, and $Q2$, $S1$, and $O1$ have direct routes to plant position $P2$. However, $J2$ does not have a direct route to $P1$ or $P2$, accessing the plants from the main road.

Similar to the model of Lima *et al.* (2013), the proposed approach also supports the decision of what manufacturing plant should be constructed and where it should be located. However, I have defined that positions can be utilized for either setting up soil-aggregate mixing plants, or HMA manufacturing plants, or both. For instance, in Figure 16, both types of plants can be constructed at positions $P1$ and $P2$, once all the necessary resources for producing soil-aggregate mix and HMA can be transported to these plants. In addition, the two plants can be simultaneously built as long as the costs of plant construction are lower than the savings in logistics costs.

Following the literature analysis in Section 3.3.2, I did not include a path location model or algorithm because the process would be ineffective once the analyzed segment presents limitations in land use, including dense urban areas, rural settlements, and environmental protection areas. As a result, I decided to focus on evaluating the existing alternatives, following the studies on the economic, technical, and environmental feasibility of CE-085 road (DER-CE, 2012).

3.4.2 Construction Costs

All the unit costs used in this study followed the *System of Referential Construction Costs* (SICRO) of the *National Department of Transportation Infrastructure* (DNIT) (DNIT, 2020), as detailed in Appendix B. I chose SICRO because is the only Brazilian cost system which details transportation costs based on the surface type of the road (unpaved, gravel, or HMA surface).

I assumed that the unit costs related to Levels 1 and 2 (Figure 15) were the total costs for excavating, transporting, and compacting soil. Following DNIT (2020), I assumed that the excavation cost depends on the type of soil. Consequently, I considered a set of soil types N according to the classification of DNIT (2020), which divided soils into three distinct categories ($n \in N$) related to the diameter of particles (D_{part}) and the volume of rocks found in the soil (V_{Rock}) (DNIT, 2009a), as shown in Table 10.

In contrast to excavation, as mentioned before, DNIT (2020) set distinct costs for transportation based on the surface type. As a result, I considered that all allocations on the main road were made on an unpaved surface. For allocations on haul roads, I included a new set V related to the chosen surface type ($v \in V$).

Table 10 – Soil types $n \in N$

Soil Category	Diameter of Soil Particles	Rock Volume
Category 1 (n = 1)	$D_{part} < 0.15$ m	-
Category 2 (n = 2)	0.15 m $\leq$ $D_{part} < 1.00$ m	V < 2 m^3
Category 3 (n = 3)	$D_{part} \geq 1.00m$	V $\geq$ 2m^3

Source: Author

In Level 3, two-unit costs were considered. First, I considered the cost of obtaining raw materials and transporting them from quarries to plants. Second, I also included the cost of processing, transporting, and compacting manufactured material (soil aggregate mix and HMA).

Apart from unit costs, I also calculated the construction costs of each haul road and processing plant. Following DNIT (2020), I included the cost of cleaning, leveling, and compacting for haul road construction and the cost of installation for processing plant implementation.

3.4.3 Modeling

3.4.3.1 Objective Function

I developed an objective function that minimizes the total costs of earthmoving and paving operations, including the three different levels of allocation (Figure 5), as shown in Equation 1.

$$\begin{aligned} Minimize\ Z = & \sum_i \sum_j \sum_n \sum_o C_{ijno} X_{ijno} + \sum_k \sum_j \sum_n \sum_o \sum_s \sum_v CB_{kjnosv} XB_{kjnosv} \\ & + \sum_i \sum_m \sum_n \sum_p CP_{imnp} XP_{imnp} + \sum_k \sum_m \sum_n \sum_p \sum_s \sum_v C\beta_{kmnpsv} X\beta_{kmnpsv} \\ & + \sum_i \sum_k \sum_n \sum_s \sum_v CS_{iknsv} XS_{iknsv} + \sum_w \sum_r \sum_q \sum_s \sum_v CQ_{wrqsv} XQ_{wrqsv} + \sum_r \sum_m \sum_u CA_{rmu} XA_{rmu} \\ & + \sum_r \sum_s \sum_v YB_{ksv} PB_{ksv} + \sum_r \sum_u YP_{ru} PP_{ru} + \sum_w \sum_s \sum_v YQ_{wsv} PQ_{wsv} + \sum_r YA_r PA_r \end{aligned} \tag{1}$$

The notation for costs and decision variables related to the allocation of Levels 1 and 2 is as follows:

- C_{ijno}: Unit cost in USD/m^3 to allocate soil type n from cut section i to layer o of fill section j;

- X_{ijno}: Volume of soil type n in m^3 moved from cut section i to layer o of fill section j;
- CB_{kjnosv}: Unit cost in USD/m^3 to allocate soil type n from borrow pit k to layer o of fill section j on haul road s with surface type v;
- XB_{kjnosv}: Volume of soil type n in m^3 moved from borrow pit k to layer o of fill section j on haul road s with pavement type v;
- CP_{imnp}: Unit cost in USD/m^3 to allocate soil type n from cut section i to layer p of pavement segment m;
- XP_{imnp}: Volume of soil type n in m^3 moved from cut section i to layer p of pavement segment m;
- $C\beta_{kmnpsv}$: Unit cost in USD/m^3 to allocate soil type n from borrow pit k to layer p of pavement segment m on haul road s with surface type v;
- $X\beta_{kmnpsv}$: Volume of soil type n in m^3 moved from borrow pit k to layer p of pavement segment m on haul road s with surface type v;
- CS_{iknsv}: Unit cost in USD/m^3 to allocate discarded soil type n from cut section i to excavated borrow pit k on haul road s with pavement type v;
- XS_{iknsv}: Discarded soil type n moved from cut section i to excavated borrow pit k on haul road s with surface type v.

For Level 3, I included a new set Q related to the type of raw material ($q \in Q$) transported from quarries ($w \in W$) to plants (located in $r \in R$). I included the decision variable XQ_{wrqsv} (in $tons$) that corresponds to the moved raw material type q from quarry w to a plant located in r on haul road s with surface type v. Furthermore, I also incorporated the associated cost CQ_{wrqsv} (in USD/ton) in the objective function.

In contrast to allocations involving borrow pits and quarries, I assumed that allocations from plants to pavement segments follow just one access path to the main road. The plants are generally constructed close to the construction site to efficiently deliver manufactured material to the pavement layers. As a result, there is no effective difference in considering more than one haul road per plant. Hence, I did not include the dimensions s and v for allocations from plant positions ($r \in R$) to layers ($u \in U$) in pavement segments ($m \in M$), using XA_{rmu} (in $tons$) and CA_{rmu} (in USD/ton) as the decision variable and associated cost.

Furthermore, I considered these haul roads with a gravel surface pavement because it needs to support a considerable volume of equipment traffic.

To include the construction costs of haul roads and processing plants, I included four

Boolean variables. These decision variables indicate whether haul road s or plants located in r were constructed (1) or not (0), forcing the construction costs to be added or removed from the total costs in the objective function. As a result, I use the notation in Equation 1:

- $YB_{ksv} \in \{1,0\}$: Boolean variable that indicates whether haul road s with surface type v is constructed to connect the borrow pit k to a certain destination;
- PB_{ksv}: Construction cost (USD) of haul road s with surface type v used to connect a borrow pit k to a certain destination;
- $YQ_{wsv} \in \{1,0\}$: Boolean variable that indicates whether haul road s with surface type v is constructed to connect quarry w to a certain destination;
- PQ_{wsv}: Construction cost (USD) of haul road s with surface type v used to connect a quarry w to a certain destination;
- $YP_{ru} \in \{1,0\}$: Boolean variable that indicates whether the processing plant is installed in position r in order to produce manufactured material for the construction of layer u;
- PP_{ru}: Construction cost (USD) of the processing plant in position r that produces manufactured material for the construction of layer u;
- $YA_r \in \{1,0\}$: Boolean variable that indicates whether position r is being used by processing plants;
- PA_r: Construction cost of the haul road between plant position r and the main road.

3.4.3.2 Volume Constraints

I formulated the volume constraints with the objective of guaranteeing the volume balance in both earthmoving and paving operations. First, I set Equation 2, which ensures that all volumes originating from each cut section (VC_{in}) must be used or discarded, as shown below:

$$\sum_{j}\sum_{o} X_{ijno} + \sum_{k}\sum_{s\in Sb(k)}\sum_{v} XS_{iknsv} + \sum_{m}\sum_{p} XP_{imnp} = VC_{in}, \ \ \forall i \in I, \ \ \forall n \in N \qquad (2)$$

where $Sb(k)$ is the subset of S ($Sb(k) \subset S$), which represents the haul roads alternatives contained in each borrow pit k. After that, I wrote Equations 3 and 4 to certify that the volumes of fill sections and pavement segments (Level 2) must be completely filled by material from cut sections and borrow pits, as follows:

$$\sum_{i}\sum_{n} X_{ijno}\,\varphi_{ijno} + \sum_{k}\sum_{n}\sum_{s\in Sb(k)}\sum_{v} XB_{kjnosv}\,\varphi B_{kjno} = VF_{jo},\ \ \forall j \in J,\ \forall o \in O \tag{3}$$

$$\sum_{i}\sum_{n} XP_{imnp}\,\varphi P_{imnp} + \sum_{k}\sum_{n}\sum_{s\in Sb(k)}\sum_{v} X\beta_{kmnpsv}\,\varphi\beta_{kmnp} = VP_{mp},\ \ \forall m \in M,\ \forall p \in P \tag{4}$$

where:

- φ_{ijno}: Shrinkage/swell factor of soil type n moved from cut section i to layer o of fill section j;
- φB_{kjno}: Shrinkage/swell factor of soil type n moved from borrow pit k to layer o of fill section j;
- φP_{imnp}: Shrinkage/swell factor of soil type n moved from cut section i to layer p of pavement segment m;
- $\varphi\beta_{kmnp}$: Shrinkage/swell factor of soil type n moved from borrow pit k to layer p of pavement segment m;
- VF_{jo}: Volume demanded in layer o of fill section j;
- VP_{mp}: Volume demanded in layer p of pavement segment m.

In Equation 5, I assumed that the sum of the soil volume of a borrow pit k utilized in earthmoving and paving allocations must be less than or equal to the available volume of the corresponding borrow pit (VB_{kn}).

$$\sum_{j}\sum_{o}\sum_{s\in Sb(k)}\sum_{v} XB_{kjnosv} + \sum_{m}\sum_{p}\sum_{s\in Sb(k)}\sum_{v} X\beta_{kmnpsv} \le VB_{kn},\ \ \forall k \in K,\ \forall n \in N \tag{5}$$

As mentioned in Section 3.4.1.1, I considered the trenches left after excavation of borrow pits as disposal areas. Therefore, I included a new constraint (Equation 6) that imposes the volume balance between the discarded material (XS_{iknsv}) and the available volume for material disposal, which corresponds to the sum of the soil volume excavated from borrow pit k, as presented below:

$$\sum_{i}\sum_{n}\sum_{s\in Sb(k)}\sum_{v} XS_{iknsv}\,\varphi S_{ikn} \le \sum_{j}\sum_{n}\sum_{o}\sum_{s\in Sb(k)}\sum_{v} XB_{kjnosv} + \sum_{m}\sum_{n}\sum_{p}\sum_{s\in Sb(k)}\sum_{v} X\beta_{kmnpsv}, \quad \forall k \in K \tag{6}$$

where φS_{ikn} is the shrinkage/swell factor of soil type n moved from cut section i to borrow pit k.

In opposition to levels 1 and 2, I followed the constraints of Choudhari and Tindwani (2017) for Level 3. First, I set the sum of the allocated raw material q obtained from a quarry w to be less than or equal to the quantity of raw material in $tons$ (VQ_{wq}) available in the corresponding quarry w (Equation 7). Second, I assumed that the allocated raw material from each quarry (XQ_{wrqsv}) to be equal to the material proportion used to produce the processed material utilized in layers u of pavement segments m (Equation 8). Finally, I set Equation 9 to ensure that the volumes of pavement segments (Level 3) must be completely filled with the material from processing plants r.

$$\sum_{r} \sum_{s \in Sq(w)} \sum_{v} XQ_{wrqsv} \leq VQ_{wq}, \ \forall w \in W, \ \forall q \in Q \tag{7}$$

$$\sum_{w} \sum_{s \in Sq(w)} \sum_{v} XQ_{wrqsv} = \sum_{m} \sum_{u} XA_{rmu} \alpha_{qu}, \ \forall r \in R, \ \forall q \in Q \tag{8}$$

$$\sum_{r} XA_{rmu} \varphi A_{u} = VA_{mu}, \ \forall m \in M, \ \forall u \in U \tag{9}$$

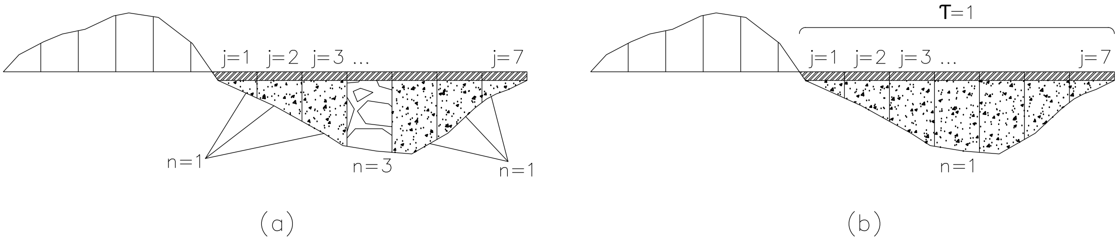
For equations 7, 8, and 9, I utilized the following notation:

- $Sq(w) \subset S$: The subset of haul road alternatives contained in each quarry w;
- α_{qu}: Proportion of raw material q used to produce the soil-aggregate mix or HMA for the construction of layers u;
- φA_u: Conversion rate of material used in the construction of layer u in $m^3/tons$;
- VA_{mu}: Volume demanded in layer u of pavement segment m.

3.4.3.3 Geotechnical Constraints

I added five new constraints (Equations 10 to 14) with the objective of complying with the highway construction characteristics and specific requirements of the CE-085 project. Initially, I observed that the division of fill sections suggested by authors Mayer and Stark (1981), Jayawardane and Harris (1990), and Lima *et al.* (2013) failed to consider the use of different types of soil in the execution of consecutive fill sections. For instance, in Figure 17 (a), I found that a long fill area with several consecutive fill sections can be filled with alternating types of soil without technical control of the execution. Consequently, I created a constraint (Equation 10) in order to guarantee that a long fill area must be executed with the same type of soil, fulfilling the technical requirements of earthmoving operations, as shown in Figure 17 (b).

Figure 17 – (a) Set of fill sections composed of different types soil (b) Set of fill sections composed of one type soil



Source: Author

In Equation 10, I introduced a new set T of fill areas, a subset $J(\tau)$ of consecutive fill sections contained in a fill area $\tau \in T$, and a new Boolean variable YF_{tno}. This new Boolean variable determines which type of soil n is used in fill area t. As an example, in Figure 17, if a soil type $n = 1$ is used in layer $o = 2$ of any consecutive fill sections $j \in J(1) = \{1,...,7\}$ of fill area $\tau = 3$, $YF_{3,1,2}$ must be equal to 1. Consequently, I included an upper bound $\left(\sum_{j \in J(\tau)} VF_{jo}\right)$ in order to force YF_{tno} to be assigned as 1 when soil type n is used, and 0 otherwise.

$$\sum_{i} \sum_{j \in J(\tau)} X_{ijno}\, \varphi_{ijno} + \sum_{k} \sum_{j \in J(\tau)} \sum_{s \in Sb(k)} \sum_{v} XB_{kjnosv}\, \varphi B_{kjno} \leq \left(\sum_{j \in J(\tau)} VF_{jo} \right) \times YF_{\tau no}, \quad \forall \tau \in T,\ \forall n \in N,\ \forall o \in O \tag{10}$$

I also included another constraint (Equation 11) to ensure that only one type of soil type n can be used in a layer o of a fill area τ, as shown in Figure 17 (b).

$$\sum_{n} YF_{\tau no} = 1,\ \forall \tau \in T,\ \forall o \in O \tag{11}$$

Equations 12, 13, and 14 represent the constraints related to the geotechnical requirements shown in Section 3.4.1.1. Thus, the soil allocations that do not entirely fulfill specifications are considered null, as presented below:

$$\sum_{i \in I(n,o)} \sum_{j} X_{ijno} + \sum_{k \in K(n,o)} \sum_{j} \sum_{s \in Sb(k)} \sum_{v} XB_{kjnosv} = 0,\ \forall n \in N,\ \forall o \in O \tag{12}$$

$$\sum_{i}\sum_{m}\sum_{n\in N_{pav}}\sum_{p}XP_{imnp}+\sum_{k}\sum_{m}\sum_{n\in N_{pav}}\sum_{p}\sum_{s\in Sb(k)}\sum_{v}X\beta_{kmnpsv}=0 \tag{13}$$

$$\sum_{i\in I(p)}\sum_{m}\sum_{n}XP_{imnp}+\sum_{k\in K(p)}\sum_{m}\sum_{n}\sum_{s\in Sb(k)}\sum_{v}X\beta_{kmnpsv}=0,\ \forall p\in P \tag{14}$$

where:

- $I(n,o) \subset I$: Subset of cut sections with soil n that do not fulfill the construction requirements of layer o;
- $K(n,o) \subset K$: Subset of borrow pits with soil n that do not fulfill the construction requirements of layer o;
- $N_{pav} \subset N$: Subset of soil types that cannot be used in pavement layers of Level 2, following the specifications of CE-085 project (DER-CE, 2012) where soil types $n = 2$ and $n = 3$ are excluded from reinforcement and sub-base layers. Thus, $N_{pav} = \{2,3\}$;
- $I(p) \subset I$: Subset of cut sections that do not fulfill the construction requirements of layer p;
- $K(p) \subset K$: Subset of borrow pits that do not fulfill the construction requirements of layer p.

3.4.3.4 Haul Road Selection Constraints

For haul road construction, I created two Boolean variables (YB_{ksv} and YQ_{wsv}) to indicate whether haul roads need to be constructed to link borrow pits and quarries to final (fill sections and pavement segments) or intermediary destinations (processing plants). Similar to Equation 10, I introduced inequalities to ensure that all the volume moved from a borrow pit or quarry must be less than or equal to an upper bound equivalent to the available volume of the corresponding borrow pit or quarry, as shown in Equations 15 and 16. Thus, if there is any movement from a borrow pit or quarry to a any source of demand, the corresponding Boolean variable would assign a value of 1; otherwise, it would assign a value of 0.

$$\sum_{j}\sum_{n}\sum_{o}XB_{kjnosv}+\sum_{m}\sum_{n}\sum_{p}X\beta_{kmnpsv}+\sum_{i}\sum_{n}XS_{iknsv}\leq\left(\sum_{n}VB_{kn}\right)\times YB_{ksv},$$
$$\forall k\in K,\ \forall s\in Sb(k),\ \forall v\in V \tag{15}$$

$$\sum_r \sum_q XQ_{wrqsv} \leq \left(\sum_q VQ_{wq} \right) \times YQ_{wsv}, \ \forall w \in W, \ \forall s \in Sq(w), \ \forall v \in V \tag{16}$$

I also added two new constraints (Equations 17 and 18) related to the chosen type of surface of haul road s, imposing that just one type v must be utilized during construction.

$$\sum_v YB_{ksv} \leq 1, \ \forall k \in K, \ \forall s \in Sb(k) \tag{17}$$

$$\sum_v YQ_{wsv} \leq 1, \ \forall w \in W, \ \forall s \in Sq(w) \tag{18}$$

As a result, the sum of Boolean variables $\sum_v YB_{ksv}$ and $\sum_v YQ_{wsv}$ would be equal to 1 if the corresponding haul road s is being used, inducing the model to choose only one type of surface v for haul road s of borrow pit k or quarry w; otherwise, $\sum_v YB_{ksv}$ and $\sum_v YQ_{wsv}$ would be null, indicating that haul road s is not being used for material allocation.

3.4.3.5 HMA and Soil-aggregate Mixing Constraints

In Section 3.4.3.1, I introduced the Boolean variable YP_{ru}, which indicates whether the processing plant is installed at position r in order to produce manufactured material for the construction of layer u. In other words, YP_{ru} presents the type of plant (HMA or soil-aggregate mixing) installed in position r. Therefore, I introduced a new constraint (Equation 19) to determine the YP_{ru} value.

$$\sum_m XA_{rmu} \varphi A_u \leq \left(\sum_m VA_{mu} \right) \times YP_{ru}, \ \forall r \in R, \ \forall u \in U \tag{19}$$

Similar to Equations 15 and 16, this constraint is based on an inequality where the maximum transportable volume is the upper bound. As a consequence, YP_{ru} assigns a value of 1 when material from plant position r is transported to layer u, indicating that a plant that produces material compatible with layer u was installed at position r. On the other hand, YP_{ru} would assign a value of 0 when there is no allocations between plant position r and layer u, indicating that a plant compatible with layer u was not installed in position r.

In Section 3.4.3.1, I also mentioned that I considered just one haul road with gravel surface for transporting processed material from plant position r to pavement layer u. As a result, I created another constraint (Equation 20) to determine the value of YA_r and the associated haul road construction cost. In short, YA_r indicates whether position r is being used by any type of processing plant. Thus, it also shows whether the processing plant's haul road should be constructed.

$$\sum_{u} YP_{ru} \leq 2 \times YA_r, \ \ \forall r \in R \tag{20}$$

As presented in Equation 20, I used the sum of YP_{ru} to verify whether any type of processing plant is being utilized in position r. In addition, I used the maximum possible value of $\sum_u YP_{ru}$ as the upper bound. Thus, for all $r \in R$, $max(\sum_u YP_{ru}) = 2$, once I consider two types of plants in this problem (soil-aggregate mix and HMA processing plants).

3.5 Case Study

After structuring and modeling the problem, I applied an optimization approach to the CE-085 road project. Initially, I identified all cut and fill sections, pavement segments, and external sources. The analyzed project has 121 cut sections, 257 fill sections, 272 pavement segments, 26 borrow pits, two plant positions, one oil refinery, and five quarries (two coarse aggregate quarries, two soil quarries, and one sand quarry).

Following the studies on economic, technical, and environmental feasibility of CE-085 road (DER-CE, 2012), I located the external sources (borrow pits, quarries, pant positions, and refinery), presenting possible alternatives for haul road construction, as shown in Figure 18.

During the project analysis, I also observed that quarries $w = 1$, $w = 3$, and $w = 4$, and oil refinery $w = 2$ were far from the CE-085 road. Therefore, the raw material has the necessity to be transported on other roads (Figure 19 (a)). Thus, I included an extra cost in CQ_{wrqsv} associated with transportation on paved highways, as presented in Appendix B.

Although the haul roads of these quarries do not have access points to processing plants or to the main road, I also considered the construction costs of haul roads used to link these sources to the auxiliary roadways. As an example, in Figure 19 (b) and (c), the coarse aggregate quarry $w = 4$ and the sand quarry $w = 1$ present a haul road connecting the aggregate

Figure 18 – (a) CE-085 road layout (b) Haul roads associated to external sources (borrow pits, quarries, and plant positions)

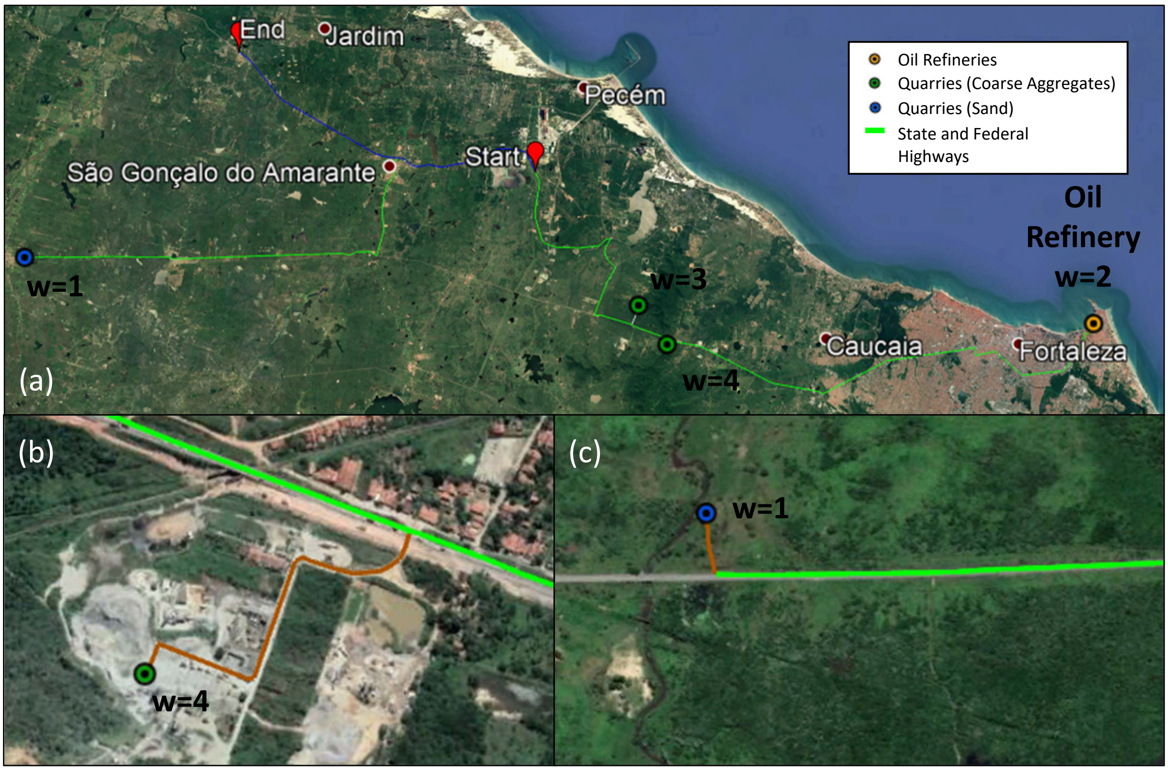
Source: Adapted from Google Earth (2020)

source to an auxiliary road (BR-222 road). Consequently, the cost of construction for these haul roads was included in the PQ_{wsv} array as well as any other haul road associated with quarries.

After analyzing the CE-085 projects and surveys, I defined all data inputs, computing shrinkage/swell factors, volumes, construction costs, and geotechnical conditions, as detailed in Appendix C. As a result, I used the calculated inputs to run the proposed MILP model in IBM CPLEX version 12.10.0 on a PC with an Intel Core I7 2.6 GHz processor and 12 GB of memory. Following the calculated costs based on DNIT (2020), I obtained a solution with a total cost of $Z =$ USD 4,743,775.58 in 2.98 s, given in a detailed manner in Appendix D.

With the full results, I can identify whether the inclusion of haul roads was relevant in road construction logistics. Therefore, I investigated the results related to the Boolean variables YB_{ksv} and YQ_{wsv}, to find out the most economical option. In general, the chosen alternative was the shortest path between the source and destination, including 13 of the 16 sources with more than one haul road option. However, I found that, in three borrow pits ($k = 13$, $k = 16$, and $k = 17$), the model assigned a value of one for the two presented alternatives. Thus, the model evaluated that constructing both path options would result in reduction of allocations

Figure 19 – (a) External sources far from CE-085 road (b) Haul road connecting coarse aggregate quarry $w = 4$ to BR-222 road (c) Haul road connecting sand quarry $w = 1$ to BR-222 road



Source: Adapted from Google Earth (2020)

costs greater than the construction of the costly alternative. In that case, the cost reduction was greater than USD 85.26 for allocations from borrow pits k = 13, USD 237.15 for allocations from borrow pits k = 16, and USD 144.93 for allocations from borrow pits k = 17.

I also analysed the results related to the choice of position for plant installation. As shown in Figure 18 (a), I considered two plant positions based on the DER-CE (2012). As a result, the solution decided to the first position ($r = 1$) located on Km 19.0 near to the city of São Gonçalo do Amarante where the soil-aggregate mix and HMA processing plants were installed. Hence, I confirmed that position $r = 1$ was the best location for supplying material to Level 3 allocations once it is more centrally located in the construction site layout. Furthermore, I also inferred that it is not advantageous to install other plants at position $r = 2$ if the cost reduction in material transportation does not pay back the installation cost of a soil-aggregate mix plant (USD 12,680.78) or HMA plant (USD 23,074.46).

3.6 Conclusions

In this paper, I described an optimization approach to plan earthmoving and paving operations which considers engineering features such as haul road selection, geotechnical constraints, and material manufacturing (soil-aggregate mix and HMA). In general, the model was able to obtain cost-efficient solutions with a satisfactory level of detail, including both logistics (earthmoving and paving allocations) and infrastructure costs (haul roads and plant construction).

Similar to the studies of Mayer and Stark (1981), Easa (1987), Jayawardane and Harris (1990), and Gwak *et al.* (2018), a MILP approach was adopted based on the transportation problem. Following the past research of Lima *et al.* (2013) and Bogenberger *et al.* (2015), I could expand a classical problem, creating a coherent model that reflects the practical necessities of road construction. In summary, this model is able to work with the allocation of different materials (e.g., aggregates, asphalt, and soil), incorporating constraints related to material mixing and processing. However, the main contribution of the model is the addition of novel decision variables related to route choices. Therefore, the proposed model is able to deal with the decision of which haul road alternative should be utilized, considering the construction costs associated with the proposed alternatives.

In contrast to past routing problems, the model is not computationally expensive and requires fewer resources, such as time and computer memory. Although I did not work with detailed sensitive analysis of the model performance, I observed that the proposed model could easily solve realistic problems in a short time. For instance, the model solved a case study with 155 sources and 529 destinations in less than 3 s.

Also in the case study analysis, I confirmed that the model can systematically analyze the construction site logistics, choosing any one of the given options or even all the suggested alternatives to provide a reduction in the allocation costs. Based on that, I could infer that the inclusion of more alternatives can generate savings in material transportation since the proposed model will have more allocations to be analysed. Thus, future research can perform a detailed economic analysis, evaluating the economic impact of gradually including more haul road alternatives in some test scenarios.

Among the limitations, I also identified that the considered haul road construction costs (DNIT, 2020) overlook some important engineering aspects. In contrast to Kang and Seo (2013), characteristics like ground slope, geotechnical conditions of the subgrade, and environmental impacts are not incorporated in neither the costs or the selection of alternatives. Therefore, I suggest that forthcoming research can develop a methodology able to consider the above-mentioned criteria in haul roads budgeting, making model's application more consistent with reality.

4 GENERAL CONCLUSIONS

4.1 Final Considerations

In this dissertation, I proposed to develop an optimization model for minimizing the costs of earthmoving operations, considering distinct engineering features in modeling. Specifically, I included aspects related to road construction into the decision variables and constraints, considering the geotechnical specifications, details of paving operations and haul road selection. My main objective was to provide an optimization approach close to real-world applications, facilitating its use in road construction planning.

Complying with this research objective, I divided this dissertation into two distinct parts. First, I systematically analysed the literature to integrate past contributions, aiming to find opportunities for improving optimization approaches related to earthmoving operations. Second, I developed an optimization model for road construction based on the research trends presented in the proposed systematic mapping study.

In my mapping study, I sought to find as many relevant studies as possible. Consequently, I performed a systematic review based on automatic searches and snowballing sampling, finding more than 5000 results, from which I selected 72 papers between 1958 and 2019. After deeply analyzing the selected studies, I could observe that the large majority of the research on optimization of earthmoving operations focuses on minimizing costs of material allocation in construction.

Generally, the first proposed approaches adapted classical problems for optimally perform trade-offs between cut and fill sections. Soon after, researchers have developed mathematical models capable of solving complex problems, involving operations sequencing, discretization of processes and temporary interruption of allocations by obstacles. However, few studies brought constructive aspects and the experience of specialized professionals, limiting the applicability of the proposed models in real-world projects. Therefore, I could conclude that this limitation is associated with the fact that the optimization techniques are not primarily utilized by road construction professionals, once most of the models overlook geotechnical conditions and requirements demanded for execution of earthmoving and paving layers.

Based on these mapping study findings, I decided to focus on the development of a efficient transportation model able to plan material allocation related to both earthmoving and paving operations. Following road construction logistics, I choose to divide the allocations into distinct material flows. As a result, I created two allocation flows to transport non-processed material to earthmoving and pavement layers, and an allocation flow to transport processed materials to base layers and asphalt surface, considering an intermediary destination for mixing and processing raw material obtained in quarries. Subsequently, I created the constraints related to geotechnical aspects of construction, ensuring that only the material that meets the quality requirements of a layer should be utilized for filling that type of layer.

In addition to the above-mentioned contributions, I also considered construction of haul roads in modeling. In contrast to the past allocation approaches, I realized that the material from external sources can be transported in different routes, accessing distinct points of the construction site and generating distinct allocation costs. Consequently, I concluded that an accurate representation of construction logistics needs to include a detailed analysis of the routes utilized in allocation flows. Therefore, I incorporated the variables related to the decision of what path should be constructed and its associated costs in the objective function.

After modeling the proposed solution, I validated the optimization approach using data of a real project on a 27.84 km long road in the State of Ceará, Brazil. Complying with the research objectives, the model presented reasonable results, generating the global cost, allocated volumes, and selected routes as outputs. According to these values presented, I confirmed that the model systematically analyzes the haul road alternatives, evaluating whether the distance reduction in allocation generated by a new route pays for the costs of its construction. For instance, in three distinct situations of the case study, the model chose to build all alternatives once the savings in allocation were greater than the sum of the respective haul road construction costs.

Although the study fulfilled all research goals listed in Chapter 1, I identified three limitations related to construction costs and the performance analysis of the proposed model. First, the costs utilized for haul road construction do not compute the influence of ground slope, geotechnical conditions of the subgrade, and possible environmental impacts of construction. Second, the study did not use randomly generated instances for testing processing times, limiting the analysis of computational model performance. Finally, the study did not verified the influence of the number of haul road alternatives in costs savings, failing to evaluate the economic impact of gradually including alternatives in a project scenario.

4.2 Recommendations for Future Research

Based on sections 2.6 and 3.6, I summarized the following recommendations for future research in the field:

4.2.1 First Article: Optimization of Earthmoving Planning and Operation: A Mapping Study

- Develop integrative literature reviews for the four main research topics (earth allocation planning, equipment fleet planning, earthmoving operations routing, and earthmoving operations scheduling), comparing the performance of the proposed mathematical models.
- Investigate the benefits and impacts of using optimization techniques after planning and pre-construction stages, evaluating the adaptability of the proposed models to sudden changes in the construction project.
- Incorporate the experience of specialized professionals to improve the applicability of the models.
- Propose optimization models that consider environmental impacts in their constraints and objective functions, minimizing fuel consumption and emissions of greenhouse gases.
- Include constraints that ensure sustainable use of resources, encouraging material reuse and recycling, and reducing the use of disposal areas.

4.2.2 Second Article: Optimization of Earthmoving and Paving Operations in Road Construction: Allocation Model Considering Multiple Temporary Haul Roads

- Create a methodology to better price the construction of haul roads, including aspects like ground slope and subgrade conditions.
- Perform a detailed economic analysis of the allocation model's results, evaluating the economic impact of gradually including more haul road alternatives in a test scenario.
- Investigate the computational performance of the proposed allocation model by using randomly generated instances.

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5 APPENDIX A - ANSWERS TO RESEARCH QUESTIONS

In Appendix A, I showed the detailed answers to each research question, considering all selected papers, as presented in Table 11.

Table 11 – Selected papers

Paper	Authors	RQ1	RQ2	RQ3	RQ4	RQ5		RQ6	
FT01	Mayer and Stark (1981)	EAP	Min. Cost	MILP	SP	A	R	USA	J
FT02	Nandgaonkar (1981)	EAP	Min. Distance	LP	EP	I	DE	Afghanistan	J
FT03	Perry and Iliff (1983)	EAP	Min. Distance	LP	EP	I	A	Australia	J
FT04	Easa (1987)	EAP	Min. Cost	MILP	SP	A	R	Canada	J
FT05	Christian and Caldera (1988)	EAP	Min. Cost	LP	SP	A	R	Canada	J
FT06	Easa (1988)	EAP	Min. Cost	MIQP	SP	A	R	Canada	J
FT07	Jayawardane and Harris (1990)	EAP	Min. Cost	MILP	SP	A	R	UK	J
FT08	Jayawardane and Price (1994a)	EAP	Min. Cost	MILP	SP	B	R	Sri Lanka	P
FT09	Moreb and Bafail (1994).	EAP	Min. Cost	LP	SP	A	G	Saudi Arabia	J
FT10	Jayawardane and Price (1994b)	EAP	Min. Cost	MILP	VR	B	R	Sri Lanka	P
FT11	Marzouk and Moselhi (2002)	EFP	Min. Cost	GA	SP	B	D	Canada	J
FT12	Henderson *et al.* (2003)	EOR	Min. Distance	SA	SP	A	G	USA	J
FT13	Marzouk and Moselhi (2003)	EFP	Min. Cost	GA	SP	A	G	Canada	J
FT14	Marzouk and Moselhi (2004)	EFP	Min. Cost and Time	GA	SP	A	G	Canada	J
FT15	Lim *et al.* (2005)	EOR	Min. Distance	TS+SA	SP	A	G	Hong Kong	J
FT16	Songshan *et al.* (2005)	EOR	Min. Distance	CB	SP	A	G	M. China	P
FT17	Son *et al.* (2005)	EAP	Min. Momentum	LP	SP	B	G	South Korea	J
FT18	Moselhi and Alshibani (2007b)	EFP	Min. Cost and Time	GA	SP	A	G	Canada	J
FT19	Tam *et al.* (2007)	EOR	Min. Cost	GA	SP	B	G	Hong Kong	J
FT20	Karimi *et al.* (2007)	EAP	Min. Cost	FLP	SP	A	R	Iran	J
FT21	Yan *et al.* (2008)	EAP	Min. Distance	LP	SP	B	D	M. China	P
FT22	Zhang (2008)	EFP	Min. Cost and Time	PSO	SP	A	G	M. China	J
FT23	Xianjia *et al.* (2009)	EAP	Min. Cost	PSO	SP	A	G	M. China	P
FT24	Moselhi and Alshibani (2009)	EFP	Min. Cost	GA+LP	SP	A	G	Canada	J
FT25	Ji *et al.* (2010)	EAP	Min. Earth Movements	IP	SP	B	R	Germany	J
FT26	Hare *et al.* (2011)	EAP	Min. Cost	MILP	SP	A	R	Canada	J
FT27	Xu *et al.* (2011)	EFP	Min. Cost and Time	EA	SP	B	H	M. China	J
FT28	Hsiao *et al.* (2011)	EOS	Min. Time	GA	SP	B	G	Taiwan	P
FT29	Miao *et al.* (2011)	EAP	Min. Cost	ACO	SP	A	R	M. China	J
FT30	Jrade *et al.* (2012)	EFP	Min. Cost	LP	SP	B	G	Canada	J
FT31	Alshibani and Moselhi (2012a)	EFP	Min. Cost	LP	SP	B	G	Canada	J
FT32	Liu *et al.* (2012)	EAP	Min. Cost	FLP	EP	I	D	M. China	J
FT33	Alshibani and Moselhi (2012b)	EFP	Min. Cost	GA+LP	SP	A	G	Canada	J
FT34	Nassar and Hosny (2012)	EOR	Min. Distance	PSO	SP	A	G	Egypt	J
FT35	Lin *et al.* (2012)	EOS	Min. Time	GA	SP	A	G	Taiwan	J
FT36	Chu *et al.* (2012)	EAP	Min. Cost	D&R	SP	A	G	Taiwan	J
FT37	Tian *et al.* (2012)	EAP	Min. Cost	LP	EP	I	D	M. China	J
FT38	Fu *et al.* (2013)	EFP	Min. Cost and Max. Productivity	GA	SP	B	G	Sweden	P
FT39	Abu-Samra *et al.* (2013)	EFP	Min. Cost	GA	SP	B	G	Egypt	P
FT40	Lima *et al.* (2013)	EAP	Min. Cost	MILP	SP	B	R	Brazil	J

Table 11 – Selected papers

Paper	Authors	RQ1	RQ2	RQ3	RQ4	RQ5		RQ6	
FT41	Liu *et al.* (2013)	EOR	Min. Time	LP	SP	B	G	Canada	P
FT42	Zhao *et al.* (2013)	EAP	Min. Cost	DP	SP	B	D	M. China	J
FT43	Hwang *et al.* (2014)	EOS	Min. Cost	GA	SP	A	G	South Korea	J
FT44	Burdett and Kozan (2014)	EAP	Min. Distance	SA+EA	SP	A	G	Australia	J
FT45	Burdett *et al.* (2015)	EAP	Min. Fuel/Emissions	MILP	SP	B	R	Australia	J
FT46	Parente *et al.* (2015)	EFP	Min. Cost and Time	EA	SP	B	G	Portugal	J
FT47	Bogenberger *et al.* (2015)	EAP	Min. Cost	LP	EP	I	R	Austria	J
FT48	Liu and Lu (2015)	EOR	Min. Time	LP	SP	B	G	Canada	J
FT49	Yi and Lu (2016)	EOR	Min. Cost	MILP	SP	B	G	Canada	J
FT50	Dell'Amico *et al.* (2016)	EAP	Min. Cost	LP	EP	I	R	Italy	J
FT51	Falcão *et al.* (2016)	LR	NA	NA	LR	A	NA	Brazil	J
FT52	Parente *et al.* (2016)	EFP	Min. Cost and Time	EA	SP	B	G	Portugal	J
FT53	Gwak *et al.* (2016)	EOR	Min. Time	GA	SP	A	G	South Korea	J
FT54	Naskoudakis and Petroutsatou (2016)	LR	NA	NA	LR	B	NA	Greece	J
FT55	Güden and Süral (2017)	EAP	Min. Cost	DP	SP	A	R	Turkey	J
FT56	Li and Lu (2017)	EAP	Min. Cost	LP	SP	A	G	Canada	J
FT57	Lee *et al.* (2017)	EAP	Min. Cost	LP	SP	B	R	South Korea	J
FT58	Choudhari and Tindwani (2017)	EAP	Min. Cost	LP	SP	B	R	India	J
FT59	Gwak *et al.* (2018)	EAP	Min. Cost	MILP	SP	A	R	South Korea	J
FT60	Li and Lu (2019)	EAP	Min. Cost	LP	SP	B	G	Canada	J
FT61	Yi and Lu (2019)	EOR	Min. Cost	MILP	ER	A	G	Canada	J
SB01	Kantorovitch (1958)	EAP	Min. Cost	LP	SP	A	G	Russia	J
SB02	Al-Tabtabai and Alex (1999)	EAP	Min. Cost	GA	SP	A	R	Kuwait	J
SB03	Ugwu and Tah (2002)	EOS	Min. Cost	GA	SP	B	G	Hong Kong	J
SB04	Kataria *et al.* (2005)	EAP	Min. Cost	ACO	SP	A	R	India	P
SB05	Cao *et al.* (2006)	EAP	Min. Cost	LP	EP	I	D	M. China	P
SB06	Pantouvakis and Manoliadis (2008)*	EAP	Multicriteria	CP	SP	A	R	Greece	J
SB07	Burdett and Kozan (2013)	EAP	Min. Fuel/Emissions	MILP	SP	B	R	Australia	P
SB08	Aziz and Abuol-Magd (2015)	EFP	Min. Cost	LP	EP	I	G	Egypt	J
SB09	Li *et al.* (2015)	EOR	Min. Cost	LP	SP	A	G	Canada	P
SB10	Liao *et al.* (2016)	EAP	Min. Cost	LP	SP	B	G	M. China	P
SB11	Krantz *et al.* (2017)	EAP	Min. Fuel/Emissions	LP	EP	I	G	Sweden	J

*This paper was classified as EAP due to optimization approach for selection of borrow pit sites

Source: Author.

The following notation was used in this appendix:

- FT(n): Paper selected from the first full-text analysis;
- SB(n): Paper included in the snowballing selection;
- EAP: Earth Allocation Planning;
- EFP: Equipment Fleet Planning;
- EOR: Earthmoving Operations Routing;
- EOS: Earthmoving Operations Scheduling;
- LR: Literature Review;

- ACO: Ant Colony Optimization;
- CB: Cycle-based Algorithm;
- CP: Compromise Programming;
- D&R: Decomposition and Relaxation;
- DP: Dynamic Programming;
- EA: Evolutionary Algorithm;
- FLP: Fuzzy Linear Programming;
- GA: Genetic Algorithm;
- IP: Integer Programming;
- LP: Linear Programming;
- MILP: Mixed-integer Linear Programming;
- MIQP: Mixed-integer Quadratic Programming;
- PSO: Particle Swarm Optimization;
- SA: Simulated Annealing;
- TS: Tabu Search;
- EP: Experience Paper;
- ER: Evaluation Research;
- LR: Literature Review;
- SP: Solution Proposal;
- VR: Validation Research;
- A: Academia;
- I: Industry;
- B: Both (Academia and Industry);
- A: Airport Construction;
- D: Dam Construction;
- DE: Construction of Defence Facilities;
- G: General Construction Site;
- H: Hydropower Plant Construction;
- R: Road Construction;
- J: Journal;
- P: Conference Proceedings;
- NA: Not Applicable.

6 APPENDIX B - CONSTRUCTION COSTS

I presented the references of SICRO utilized for calculating the construction costs of the objective function (Equation 1), as shown in tables 12 to 19. In Table 12, I showed all the unit costs related to C_{ijno} where I added an extra cost of hauling for allocations with distances (D) greater than 3 Km.

Table 12 – Unit costs for allocations between cut and fill sections (C_{ijno})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Excavation, hauling, and loading - D = 0-50 m ($n = 1$)	m^3	5501710	0.27
Excavation, hauling, and loading - D = 50-200 m ($n = 1$)	m^3	5502109	0.60
Excavation, hauling, and loading - D = 200-400 m ($n = 1$)	m^3	5502110	0.64
Excavation, hauling, and loading - D = 400-600 m ($n = 1$)	m^3	5502111	0.68
Excavation, hauling, and loading - D = 600-800 m ($n = 1$)	m^3	5502112	0.75
Excavation, hauling, and loading - D = 800-1000 m ($n = 1$)	m^3	5502113	0.78
Excavation, hauling, and loading - D = 1000-1200 m ($n = 1$)	m^3	5502114	0.80
Excavation, hauling, and loading - D = 1200-1400 m ($n = 1$)	m^3	5502115	0.87
Excavation, hauling, and loading - D = 1400-1600 m ($n = 1$)	m^3	5502116	0.89
Excavation, hauling, and loading - D = 1600-1800 m ($n = 1$)	m^3	5502117	0.92
Excavation, hauling, and loading - D = 1800-2000 m ($n = 1$)	m^3	5502118	0.94
Excavation, hauling, and loading - D = 2000-2500 m ($n = 1$)	m^3	5502119	1.03
Excavation, hauling, and loading - D = 2500-3000 m ($n = 1$)	m^3	5502120	1.14
Excavation, hauling, and loading - D >3000 m ($n = 1$)	m^3	5502834	1.18
Extra hauling - D >3000 ($n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5915319	0.15
Excavation, hauling, and loading - D = 0-50 m ($n = 2$)	m^3	5502187	0.69
Excavation, hauling, and loading - D = 50-200 m ($n = 2$)	m^3	5502585	0.85
Excavation, hauling, and loading - D = 200-400 m ($n = 2$)	m^3	5502586	0.90
Excavation, hauling, and loading - D = 400-600 m ($n = 2$)	m^3	5502587	0.94
Excavation, hauling, and loading - D = 600-800 m ($n = 2$)	m^3	5502588	1.04
Excavation, hauling, and loading - D = 800-1000 m ($n = 2$)	m^3	5502589	1.07
Excavation, hauling, and loading - D = 1000-1200 m ($n = 2$)	m^3	5502590	1.10
Excavation, hauling, and loading - D = 1200-1400 m ($n = 2$)	m^3	5502591	1.13
Excavation, hauling, and loading - D = 1400-1600 m ($n = 2$)	m^3	5502592	1.16
Excavation, hauling, and loading - D = 1600-1800 m ($n = 2$)	m^3	5502593	1.19
Excavation, hauling, and loading - D = 1800-2000 m ($n = 2$)	m^3	5502594	1.29
Excavation, hauling, and loading - D = 2000-2500 m ($n = 2$)	m^3	5502595	1.33
Excavation, hauling, and loading - D = 2500-3000 m ($n = 2$)	m^3	5502596	1.41
Excavation, hauling, and loading - D >3000 m ($n = 2$)	m^3	5502880	1.52
Extra hauling - D >3000 ($n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5915319	0.18
Excavation, hauling, and loading - D = 0-50 m ($n = 3$)	m^3	5502663	4.00
Excavation, hauling, and loading - D = 50-200 m ($n = 3$)	m^3	5502742	4.89
Excavation, hauling, and loading - D = 200-400 m ($n = 3$)	m^3	5502743	5.12
Excavation, hauling, and loading - D = 400-600 m ($n = 3$)	m^3	5502744	5.19
Excavation, hauling, and loading - D = 600-800 m ($n = 3$)	m^3	5502745	5.25
Excavation, hauling, and loading - D = 800-1000 m ($n = 3$)	m^3	5502746	5.30
Excavation, hauling, and loading - D = 1000-1200 m ($n = 3$)	m^3	5502747	5.35

Table 12 – Unit costs for allocations between cut and fill sections (C_{ijno})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Excavation, hauling, and loading - D = 1200-1400 m ($n = 3$)	m^3	5502748	5.40
Excavation, hauling, and loading - D = 1400-1600 m ($n = 3$)	m^3	5502749	5.44
Excavation, hauling, and loading - D = 1600-1800 m ($n = 3$)	m^3	5502750	5.64
Excavation, hauling, and loading - D = 1800-2000 m ($n = 3$)	m^3	5502751	5.69
Excavation, hauling, and loading - D = 2000-2500 m ($n = 3$)	m^3	5502752	5.77
Excavation, hauling, and loading - D = 2500-3000 m ($n = 3$)	m^3	5502753	5.90
Excavation, hauling, and loading - D >3000 m ($n = 3$)	m^3	5502886	6.13
Extra hauling - D >3000 ($n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5915319	0.23
Compaction 100% Proctor - Normal energy ($n = 1$ and $n = 2$; $o = 2$)	m^3	5502978	0.57
Compaction 100% Proctor - Normal energy ($n = 3$; $o = 2$)	m^3	5502979	1.63
Compaction 100% Proctor - Intermediary energy ($n = 1$ and $n = 2$; $o = 1$)	m^3	5503041	0.96
Compaction 100% Proctor - Intermediary energy ($n = 3$; $o = 1$)	m^3	5502822	4.74

Source: Author.

In contrast to C_{ijno}, I calculated the cost CB_{kjnosv} using an exclusive unit cost of hauling, as shown in Table 13.

Table 13 – Unit costs for allocations between borrow pits and fill sections (CB_{kjnosv})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Excavation and loading - Borrow pits ($n = 1$)	m^3	4016096	0.17
Excavation and loading - Borrow pits ($n = 2$)	m^3	4016096	0.17
Excavation and loading - Borrow pits ($n = 3$)	m^3	5502993	3.22
Hauling - Unpaved road ($v = 1$; $n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5914359	0.20
Hauling - Unpaved road ($v = 1$; $n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5914359	0.25
Hauling - Unpaved road ($v = 1$; $n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5914359	0.32
Hauling - Gravel road ($v = 2$; $n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5914374	0.16
Hauling - Gravel road ($v = 2$; $n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5914374	0.20
Hauling - Gravel road ($v = 2$; $n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5914374	0.26
Compaction 100% Proctor - Normal energy ($n = 1$ and $n = 2$; $o = 2$)	m^3	5502978	0.57
Compaction 100% Proctor - Normal energy ($n = 3$; $o = 2$)	m^3	5502979	1.63
Compaction 100% Proctor - Intermediary energy ($n = 1$ and $n = 2$; $o = 1$)	m^3	5503041	0.96
Compaction 100% Proctor - Intermediary energy ($n = 3$; $o = 1$)	m^3	5502822	4.74

Source: Author.

In allocations related to CP_{imnp} (Table 14), I considered an extra cost of placing the material from cut sections in pavement layers. This extra cost was included because soil from cuts can only be used in pavement after the conclusion of earthmoving operations. Consequently, this material needs to be deposited on the side of the road during a certain time and then replaced in the respective pavement layer.

In opposition to CP_{imnp}, I did not consider the extra cost for placing the material from the road side to pavement in $C\beta_{kmnpsv}$ calculation, as shown in Table 15. On the other hand, I included the unit costs for material transportation on temporary haul roads (unpaved and gravel surface) and on the main road (unpaved).

Table 14 – Unit costs for allocations between cut sections and pavement segments (CP_{imnp})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Sub-base - Excavation and compaction ($p = 1$)	m^3	4011227	1.24
Reinforcement - Excavation and compaction ($p = 2$)	m^3	4011211	1.24
Hauling - Unpaved road ($n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5914359	0.20
Hauling - Unpaved road ($n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5914359	0.25
Hauling - Unpaved road ($n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5914359	0.32
Placing	m^3	4413942	0.25

Source: Author.

Table 15 – Unit costs for allocations between borrow pits and pavement segments ($C\beta_{kmnpsv}$)

Activities	Unit	SICRO Reference	Price (USD/Unit)
Sub-base - Excavation and compaction ($p = 1$)	m^3	4011227	1.24
Reinforcement - Excavation and compaction ($p = 2$)	m^3	4011211	1.24
Hauling - Unpaved road ($v = 1$; $n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5914359	0.20
Hauling - Unpaved road ($v = 1$; $n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5914359	0.25
Hauling - Unpaved road ($v = 1$; $n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5914359	0.32
Hauling - Gravel road ($v = 2$; $n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5914374	0.16
Hauling - Gravel road ($v = 2$; $n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5914374	0.20
Hauling - Gravel road ($v = 2$; $n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5914374	0.26

Source: Author.

Similar to C_{ijno}, I included the unit costs related to excavation, hauling, extra hauling ($D > 3Km$), and compaction for computing the CS_{iknsv}. However, I added the unit costs for material transportation on temporary haul roads, as shown in Table 16.

Table 16 – Unit costs for allocations between cut sections and disposal areas (CS_{iknsv})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Excavation, hauling, and loading - D = 0-50 m ($n = 1$)	m^3	5501710	0.27
Excavation, hauling, and loading - D = 50-200 m ($n = 1$)	m^3	5502109	0.60
Excavation, hauling, and loading - D = 200-400 m ($n = 1$)	m^3	5502110	0.64
Excavation, hauling, and loading - D = 400-600 m ($n = 1$)	m^3	5502111	0.68
Excavation, hauling, and loading - D = 600-800 m ($n = 1$)	m^3	5502112	0.75
Excavation, hauling, and loading - D = 800-1000 m ($n = 1$)	m^3	5502113	0.78
Excavation, hauling, and loading - D = 1000-1200 m ($n = 1$)	m^3	5502114	0.80
Excavation, hauling, and loading - D = 1200-1400 m ($n = 1$)	m^3	5502115	0.87
Excavation, hauling, and loading - D = 1400-1600 m ($n = 1$)	m^3	5502116	0.89
Excavation, hauling, and loading - D = 1600-1800 m ($n = 1$)	m^3	5502117	0.92
Excavation, hauling, and loading - D = 1800-2000 m ($n = 1$)	m^3	5502118	0.94
Excavation, hauling, and loading - D = 2000-2500 m ($n = 1$)	m^3	5502119	1.03
Excavation, hauling, and loading - D = 2500-3000 m ($n = 1$)	m^3	5502120	1.14
Excavation, hauling, and loading - D >3000 m ($n = 1$)	m^3	5502834	1.18
Extra hauling - D >3000 ($n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5915319	0.15
Excavation, hauling, and loading - D = 0-50 m ($n = 2$)	m^3	5502187	0.69
Excavation, hauling, and loading - D = 50-200 m ($n = 2$)	m^3	5502585	0.85
Excavation, hauling, and loading - D = 200-400 m ($n = 2$)	m^3	5502586	0.90
Excavation, hauling, and loading - D = 400-600 m ($n = 2$)	m^3	5502587	0.94
Excavation, hauling, and loading - D = 600-800 m ($n = 2$)	m^3	5502588	1.04

Table 16 – Unit costs for allocations between cut sections and disposal areas (CS_{iknsv})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Excavation, hauling, and loading - D = 800-1000 m ($n = 2$)	m^3	5502589	1.07
Excavation, hauling, and loading - D = 1000-1200 m ($n = 2$)	m^3	5502590	1.10
Excavation, hauling, and loading - D = 1200-1400 m ($n = 2$)	m^3	5502591	1.13
Excavation, hauling, and loading - D = 1400-1600 m ($n = 2$)	m^3	5502592	1.16
Excavation, hauling, and loading - D = 1600-1800 m ($n = 2$)	m^3	5502593	1.19
Excavation, hauling, and loading - D = 1800-2000 m ($n = 2$)	m^3	5502594	1.29
Excavation, hauling, and loading - D = 2000-2500 m ($n = 2$)	m^3	5502595	1.33
Excavation, hauling, and loading - D = 2500-3000 m ($n = 2$)	m^3	5502596	1.41
Excavation, hauling, and loading - D >3000 m ($n = 2$)	m^3	5502880	1.52
Extra hauling - D >3000 ($n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5915319	0.18
Excavation, hauling, and loading - D = 0-50 m ($n = 3$)	m^3	5502663	4.00
Excavation, hauling, and loading - D = 50-200 m ($n = 3$)	m^3	5502742	4.89
Excavation, hauling, and loading - D = 200-400 m ($n = 3$)	m^3	5502743	5.12
Excavation, hauling, and loading - D = 400-600 m ($n = 3$)	m^3	5502744	5.19
Excavation, hauling, and loading - D = 600-800 m ($n = 3$)	m^3	5502745	5.25
Excavation, hauling, and loading - D = 800-1000 m ($n = 3$)	m^3	5502746	5.30
Excavation, hauling, and loading - D = 1000-1200 m ($n = 3$)	m^3	5502747	5.35
Excavation, hauling, and loading - D = 1200-1400 m ($n = 3$)	m^3	5502748	5.40
Excavation, hauling, and loading - D = 1400-1600 m ($n = 3$)	m^3	5502749	5.44
Excavation, hauling, and loading - D = 1600-1800 m ($n = 3$)	m^3	5502750	5.64
Excavation, hauling, and loading - D = 1800-2000 m ($n = 3$)	m^3	5502751	5.69
Excavation, hauling, and loading - D = 2000-2500 m ($n = 3$)	m^3	5502752	5.77
Excavation, hauling, and loading - D = 2500-3000 m ($n = 3$)	m^3	5502753	5.90
Excavation, hauling, and loading - D >3000 m ($n = 3$)	m^3	5502886	6.13
Extra hauling - D >3000 ($n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5915319	0.23
Hauling - Unpaved road ($v = 1$; $n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5915319	0.15
Hauling - Unpaved road ($v = 1$; $n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5915319	0.18
Hauling - Unpaved road ($v = 1$; $n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5915319	0.23
Hauling - Gravel road ($v = 2$; $n = 1$ - Soil density = 1.70 t/m^3)	m^3.Km	5915320	0.12
Hauling - Gravel road ($v = 2$; $n = 2$ - Soil density = 2.10 t/m^3)	m^3.Km	5915320	0.15
Hauling - Gravel road ($v = 2$; $n = 3$ - Soil density = 2.70 t/m^3)	m^3.Km	5915320	0.19
Placing and compacting	m^3	4413984	0.43

Source: Author.

As mentioned in Section 3.5, I also considered the costs of transporting raw material on paved highways, as presented in Table 17 - where $q = 1$ corresponds to sand, $q = 2$ corresponds to coarse aggregate type 0 (4.8 mm $\leq D_{part} <$ 9.5 mm), $q = 3$ corresponds to coarse aggregate type 1 (9.5 mm $\leq D_{part} <$ 19.0 mm), $q = 4$ corresponds to lime, $q = 5$ corresponds to Asphalt CAP 50/70, $q = 6$ corresponds to filler, $q = 7$ corresponds to diluted asphalt, and $q = 8$ corresponds to high quality soil.

Table 17 – Unit costs for allocations between quarries and plants (CQ_{wrqsv})

Activities	Unit	SICRO Reference	Price (USD/Unit)
Hauling - Unpaved road ($q = 1$, $q = 2$, $q = 3$, $q = 4$, $q = 6$, and $q = 8$)	ton.Km	5914359	0.12
Hauling - Unpaved road ($q = 5$ and $q = 7$)	ton.Km	5914620	0.31
Hauling - Gravel road ($q = 1$, $q = 2$, $q = 3$, $q = 4$, $q = 6$, and $q = 8$)	ton.Km	5914374	0.09
Hauling - Gravel road ($q = 5$ and $q = 7$)	ton.Km	5914621	0.25
Hauling - Paved highway ($q = 1$, $q = 2$, $q = 3$, $q = 4$, $q = 6$, and $q = 8$)	ton.Km	5914389	0.08
Hauling - Paved highway ($q = 5$ and $q = 7$)	ton.Km	5914622	0.2

Source: Author.

In Table 18, I presented the unit costs related to allocations between processing plants and pavement layers, considering a proportional cost of priming for execution of the HMA surface.

Table 18 – Unit costs for allocations between plants and pavement segments (CA_{rmu})

Activities	Unit	SICRO Reference	Price (USD/Unit)
HMA - Processing and compaction	ton	4011463	22.39
Soil-aggregate base - Processing and compaction (Adapted to 60-40% ratio)	ton	4011268	25.54
Priming - Processing and compaction (9.09 m^2 per ton of HMA)	tons of HMA	4011351	0.34
Hauling - Unpaved road	ton.Km	5914359	0.12
Hauling - Gravel road	ton.Km	5914374	0.09

Source: Author.

At last, I presented the unit costs used to price the installation of processing plants and construction of temporary haul roads, as shown in Table 19

Table 19 – Costs for construction of haul roads and plants ($PB_{ksv}, PP_{ru}, PQ_{wsv}, and PA_r$)

Activities	Unit	SICRO Reference	Price (USD/Unit)
Construction of unpaved roads (Sub-grade leveling)	m^2	4011209	0.13
Construction of gravel roads	m^3	4015612	1.29
Cleaning	m^2	5502985	0.06
HMA plant installation	unit	0903810	23074.46
Soil-aggregate mix plant installation	unit	0903808	12680.78

Source: Author.

7 APPENDIX C - CASE STUDY DATA

In Appendix C, we presented the data used in IBM CPLEX to solve the realistic instance based on CE-085 project. Initially, I defined the subsets and the index α_{qu}, as shown in tables 21 to 28.

In Table 20, I showed the cut sections $i \in I(n,o)$ that cannot be used in the construction of layers $o = 1$ and $o = 2$.

Table 20 – Cut sections $i \in$ I(n,o)

$I(n,o)$	$o = 1$	$o = 2$
$n = 1$	{1 2 3 4 5 6 7 8 29 32 33 34 35 36 37 38 39 40 42 43 44 45 46 48 49 50 51 52 53 54 56 57 65 66 67 68 69 70 88 89 94 95 96 99 116 117}	{33 34 35 36 48 49 50 51 52 53 54}
$n = 2$	{}	{}
$n = 3$	{47}	{}

Source: Author.

Similar to cut sections $i \in I(n,o)$, I presented the borrow pits $k \in K(n,o)$ that cannot be used in the construction of layers $o = 1$ and $o = 2$, as shown in Table 21.

Table 21 – Borrow pits $k \in$ K(n,o)

$K(n,o)$	$o = 1$	$o = 2$
$n = 1$	{17}	{}
$n = 2$	{}	{}
$n = 3$	{}	{}

Source: Author.

In Table 22, I showed the cut sections $i \in I(p)$ that cannot be used in the construction of pavement layers $p = 1$ and $p = 2$.

Table 22 – Cut sections $i \in$ I(p)

$I(p)$	
p=1	{1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 48 49 50 51 52 53 54 55 56 57 58 59 60 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121}
p=2	{1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 29 30 31 32 33 34 35 36 37 38 39 40 42 43 44 45 46 48 49 50 51 52 53 54 55 56 57 58 59 60 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121}

Source: Author.

I also showed the borrow pits $k \in K(p)$ that cannot be used in the construction of the pavement layers $p = 1$ and $p = 2$ (Table 23).

Table 23 – Borrow pits $k \in$ K(p)

$K(p)$	
p=1	{3 4 5 6 7 8 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26}
p=2	{3 4 5 6 7 8 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26}

Source: Author.

In Table 24, I presented all the consecutive fill sections contained in each fill area τ.

Table 24 – Fill sections $j \in J(\tau)$

τ	$J(\tau)$
1	{1 2 3 4 5 6 7 8 9 10}
2	{11 12 13 14 15 16 17 18 19 20 21}
3	{22 23 24}
4	{25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46}
5	{47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65}
6	{66 67 68}
7	{69}
8	{70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86}
9	{87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104}
10	{105}
11	{106 107 108 109 110 111 112 113}
12	{114}
13	{115 116 117}
14	{118 119 120 121 122 123}
15	{124}
16	{125 126 127 128 129 130 131}
17	{132 133 134 135 136 137 138 139 140 141 142 143 144}
18	{145 146 147 148 149 150 151 152 153 154}
19	{155 156 157 158 159 160 161 162 163}
20	{164}
21	{165 166}
22	{167 168}
23	{169 170 171 172}
24	{173}
25	{174 175 176 177 178 179 180 181 182 183}
26	{184}
27	{185}
28	{186 187 188 189 190 191 192 193 194 195 196 197}
29	{198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218}
30	{219 220 221 222 223 224}
31	{225 226}
32	{227}
33	{228}
34	{229 230}
35	{231}
36	{232}
37	{233 234 235 236 237}
38	{238 239 240}
39	{241 242 243 244 245 246 247 248}
40	{249 250 251 252 253 254 255 256}
41	{257}

Source: Author.

In Table 25, I showed the haul road alternatives for all borrow pit $k \in K$.

Similar to $Sb(k)$, I showed the haul road alternatives for all quarry $w \in W$ (Table 26).

Table 25 – Haul roads alternatives $s \in Sb(k)$

k	$Sb(k)$	k	$Sb(k)$	k	$Sb(k)$	k	$Sb(k)$	k	$Sb(k)$
1	{1}	7	{1 2}	13	{1 2}	19	{1 2}	25	{1}
2	{1}	8	{1}	14	{1}	20	{1}	26	{1 2}
3	{1 2}	9	{1}	15	{1}	21	{1 2}		
4	{1 2}	10	{1 2}	16	{1 2}	22	{1 2}		
5	{1 2}	11	{1 2}	17	{1 2}	23	{1}		
6	{1 2}	12	{1 2}	18	{1}	24	{1 2}		

Source: Author.

Table 26 – Haul roads alternatives $s \in Sq(w)$

w	$Sq(w)$	w	$Sq(w)$	w	$Sq(w)$
1	{1}	3	{1}	5	{1}
2	{1}	4	{1}	6	{1}

Source: Author.

In Table 27, I showed the proportion used in the production of HMA and soil-aggregate mix.

Table 27 – Proportion of raw material for soil-aggregate mix and HMA production

α_{qu}	u = 1	u = 2
Sand ($q = 1$)	0.49	0.00
Coarse aggregate - 4.8 mm $\leq D_{part}$ < 9.5 mm ($q = 2$)	0.09	0.00
Coarse aggregate - 9.5 mm $\leq D_{part}$ < 19.0 mm ($q = 3$)	0.09	0.40
Lime ($q = 4$)	0.06	0.00
Asphalt CAP 50/70 ($q = 5$)	0.06	0.00
Filler ($q = 6$)	0.21	0.00
Diluted asphalt CM-30 ($q = 7$)	0.01	0.00
High quality soil ($q = 8$)	0.00	0.60

Source: Author.

After determining the subsets, I defined the shrinkage/swell factors, volumes, and construction costs. However, they resulted in extremely long arrays. Consequently, I created an external source with all data utilized for running the model in the IBM CPLEX (FERNANDES, 2021).

8 APPENDIX D - CASE STUDY RESULTS

In Appendix D, I presented the results of the optimized solution generated by IBM CPLEX. First, I showed the results of YB_{ksv} (Table 28) that assign the value of 1 for the chosen haul road alternative *s* of borrow pit *k*.

Table 28 – YB_{ksv} results

k	s	v	YB_{ksv}	k	s	v	YB_{ksv}	k	s	v	YB_{ksv}
1	1	1	0	10	1	1	0	19	1	1	0
1	1	2	1	10	1	2	1	19	1	2	0
1	2	1	0	10	2	1	0	19	2	1	1
1	2	2	0	10	2	2	0	19	2	2	0
2	1	1	0	11	1	1	0	20	1	1	0
2	1	2	1	11	1	2	1	20	1	2	1
2	2	1	0	11	2	1	0	20	2	1	0
2	2	2	0	11	2	2	0	20	2	2	0
3	1	1	0	12	1	1	0	21	1	1	0
3	1	2	0	12	1	2	1	21	1	2	0
3	2	1	0	12	2	1	0	21	2	1	0
3	2	2	1	12	2	2	0	21	2	2	1
4	1	1	0	13	1	1	0	22	1	1	0
4	1	2	0	13	1	2	1	22	1	2	0
4	2	1	0	13	2	1	0	22	2	1	0
4	2	2	0	13	2	2	1	22	2	2	1
5	1	1	0	14	1	1	0	23	1	1	0
5	1	2	1	14	1	2	1	23	1	2	1
5	2	1	0	14	2	1	0	23	2	1	0
5	2	2	0	14	2	2	0	23	2	2	0
6	1	1	0	15	1	1	0	24	1	1	0
6	1	2	1	15	1	2	1	24	1	2	0
6	2	1	0	15	2	1	0	24	2	1	0
6	2	2	0	15	2	2	0	24	2	2	0
7	1	1	0	16	1	1	0	25	1	1	0
7	1	2	0	16	1	2	1	25	1	2	1
7	2	1	0	16	2	1	0	25	2	1	0
7	2	2	1	16	2	2	1	25	2	2	0
8	1	1	0	17	1	1	0	26	1	1	0
8	1	2	1	17	1	2	1	26	1	2	0
8	2	1	0	17	2	1	0	26	2	1	0
8	2	2	0	17	2	2	1	26	2	2	0
9	1	1	0	18	1	1	0				
9	1	2	1	18	1	2	0				
9	2	1	0	18	2	1	0				
9	2	2	0	18	2	2	0				

Source: Author.

Similarly, I showed the results for YQ_{wsv} (Table 29) that assigns the value of 1 for the chosen haul road alternative *s* of quarry *w*.

Table 29 – YQ_{wsv} results

w	s	v	Value	w	s	v	Value	w	s	v	Value
1	1	1	0	3	1	1	0	5	1	1	0
1	1	2	1	3	1	2	1	5	1	2	1
1	2	1	0	3	2	1	0	5	2	1	0
1	2	2	0	3	2	2	0	5	2	2	0
2	1	1	1	4	1	1	0	6	1	1	0
2	1	2	0	4	1	2	0	6	1	2	0
2	2	1	0	4	2	1	0	6	2	1	0
2	2	2	0	4	2	2	0	6	2	2	0

Source: Author.

I also presented the values assigned for the Boolean variables YP_{ru} and YA_r related to the construction of the processing plant *r* and its associated haul road, as shown in Table 30.

Table 30 – YP_{ru} and YA_r results

YP_{ru}	u=1	u=2	YA_r
r=1	1	1	1
r=2	0	0	0

Source: Author.

After presenting the results related to Boolean variables YB_{ksv}, YQ_{wsv}, YP_{ru}, and YA_r, I presented the values of the decision variables X_{ijno}, XB_{kjnosv}, XP_{imnp}, $X\beta_{kmnpsv}$, XS_{iknsv}, XQ_{wrqsv}, and XA_{rmu}. However, the IBM CPLEX generated extremely long arrays for these results. Thus, I also included these arrays in the external source of Fernandes (2021).