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Linear programming for decision-making in construction management

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Abstract:

The object of research is to analyze the effectiveness of different linear programming (LP) methods in optimizing decision-making processes in construction project management. The aim of this research is to compare the effectiveness of different LP methods in optimizing construction quality control decisions, considering cost and duration constraints. **Method.** The study applies three LP methods: the Simplex Method, the Dual Simplex Method, and the Interior Point Method. Each method is applied to a case study scenario involving a development company facing a dilemma regarding the optimal method for conducting quality control during a construction project. The LP methods are used to evaluate the computational efficiency, accuracy, and practical implications of each approach. **Results**. Through the analysis of the case study scenario, it is observed that each LP method offers unique strengths and considerations. The Simplex Method demonstrates simplicity and relatively quick convergence, making it suitable for straightforward optimization problems. The Dual Simplex Method showcases robustness in handling complex scenarios, such as degeneracy and multiple optimal solutions. Meanwhile, the Interior Point Method proves highly efficient for large-scale problems with intricate variables and constraints, offering a precise and reliable solution.

1 Introduction

Digital technological advancements in construction are driving efficiency, sustainability, and progress in the industry. Innovations enable collaborative project representation, site monitoring, design visualization, as well as improved speed and safety, durability, real-time communication, predictive analytics, and secure contract and documentation management [1]-[2]. Technological advancements in construction have revolutionized decision-making processes by enabling data-driven insights and optimizing resource allocation, leading to more informed and effective decision-making throughout the project lifecycle [3].

The balance between the traditional approach and innovation can be credited to the application of high-quality standards. The adoption of new technologies and methodologies enable improved efficiency, sustainability, and competitiveness [4], meanwhile, it is necessary to navigate the risks associated with implementing unfamiliar technologies, potential disruption to established workflows, and the upfront investment required. This dilemma requires careful consideration and strategic decision-making to find the right balance between embracing innovation and maintaining reliability and stability in construction projects [5].

The growing complexity of technological tasks and processes in construction profoundly impacts organizational structures [6]. As technologies and advanced project management software become indispensable, organizations must adapt. This adaptation often involves creating specialized teams, fostering cross-functional collaboration, and adopting flexible workflows. Additionally, investment in training and education becomes crucial to upskill employees. The authors in [7-8] stated that management of the full life cycle of construction projects is relevant to the digital transformation of the construction industry and requires a comprehensive approach. Hierarchical structures may need to decentralize to empower frontline workers, while effective change management strategies are necessary to address resistance and ensure a smooth transition [9-11]. Overall, these changes enable organizations to leverage technology effectively and drive innovation in construction projects.

In navigating complex managerial decision-making, integrating methodologies like Analytical Hierarchy Process (AHP) and linear programming is effective. AHP breaks down decisions into hierarchies, allowing for qualitative assessment of criteria and alternatives [12]. Its output, prioritized criteria, and alternatives can be integrated into linear programming. Linear programming, a quantitative optimization method, formulates an objective function based on AHP priorities, alongside decision variables and constraints. The combined model optimizes decision outcomes while considering qualitative preferences and quantitative constraints. This integration enables decision-makers to make informed decisions, balancing qualitative insights with quantitative optimization to achieve optimal results [13]-[14].

Linear programming (LP) is a mathematical optimization method used to maximize or minimize a linear objective function within a set of linear constraints. Its principles include linearity of the objective function and constraints, seeking the optimal solution within the feasible region, and ensuring feasibility and optimality. LP involves decision variables, which are manipulated to achieve the objective, and constraints that limit feasible solutions. The feasible region represents all possible solutions satisfying the constraints. LP aims to find the best solution that optimizes the objective function while adhering to the given constraints, assuming certainty in parameter values and coefficients. It's applied in various fields for resource allocation, production planning, and other managerial decisions [15]-[17].

Linear programming (LP) finds applications across decision-centric tasks in numerous fields. For instance, LP assists in optimizing resource allocation in supply chain management, production planning, and inventory management. It aids in determining the most cost-effective production mix for manufacturing companies and helps in workforce scheduling and transportation logistics. In finance, LP is utilized for portfolio optimization and asset allocation. LP also plays a role in operational research, where it optimizes routes for delivery vehicles and schedules for project management. Additionally, LP is applied in agriculture for optimal crop planning and in healthcare for resource allocation in hospitals and healthcare facilities. Overall, LP facilitates decision-making by providing efficient solutions to complex problems across various domains [18].

The object of research is to analyze the effectiveness of different linear programming (LP) methods in optimizing decision-making processes in construction project management. The goal of this research is to compare the effectiveness of different LP methods in optimizing construction quality control decisions, considering cost and duration constraints.

2 Materials and Methods

The Simplex Method is a widely used algorithm for solving linear programming (LP) problems. It starts with an initial feasible solution and iteratively moves to adjacent feasible solutions along the edges of the feasible region until an optimal solution is reached [19]. At each iteration, it pivots between basic and non-basic variables to improve the objective function value. The Simplex Method terminates when no further improvement can be made, indicating that the current solution is optimal.

The Interior Point Method is another approach for solving LP problems. Unlike the Simplex Method, which traverses along the edges of the feasible region, the Interior Point Method moves through the interior of the feasible region. It relies on iterative updates to an interior point that satisfies the Karush-Kuhn-Tucker (KKT) conditions until convergence to the optimal solution. The Interior Point Method is often more efficient than the Simplex Method for large-scale LP problems, especially those with many variables.

The Dual Simplex Method is a variation of the Simplex Method that is particularly useful when LP problems are formulated in standard form. It pivots between basic feasible solutions of the primal and dual LP problems to improve feasibility and optimality. The Dual Simplex Method is advantageous when the primal LP problem has many constraints but few variables, as it can be more efficient than the standard Simplex Method in such cases.

In selecting a linear programming method, decision-makers must consider various factors such as problem size, sparsity of constraints, and computational efficiency. The Simplex Method is a classical approach that is well-understood and suitable for small to moderate-sized LP problems. The Interior Point Method, on the other hand, is more efficient for large-scale problems with dense constraint matrices. The

Dual Simplex Method is particularly useful when LP problems are in standard form and can provide computational advantages in certain scenarios. Ultimately, the selection of the appropriate linear programming method depends on the specific characteristics and requirements of the problem at hand [16].

In this research study a development company is embarking on a construction project divided into four main stages: substructure, superstructure, engineering systems installation and finishing works. To ensure high-quality construction at each stage, the company must decide whether to employ a department dedicated to quality control of processes or contractors from specialized quality assurance organizations. The company has a budget of #500,000 for quality control activities during the estimated 18-month construction project, with each stage requiring different durations for quality control. The cost of employing contractors is estimated at #100,000 per stage, while the cost of departmental staff is estimated at #80,000 per stage. The duration for quality control by the contractor is estimated to be 2 months per stage, while the duration for departmental staff is estimated to be 3 months per stage. The objective of this is to determine the optimal method for conducting quality control during the construction project, considering cost and duration constraints. The decision will be based on linear programming analysis to maximize quality while minimizing costs and meeting project deadlines.

Simplex Method

The mathematical model is expresses in standard LP form and then solved using the Simplex Method.

Objective function is to be maximized and expressed as below:

$$Z = Q_{11} + Q_{12} + Q_{21} + Q_{22} + Q_{31} + Q_{32} + Q_{41} + Q_{42} \to max \quad (1)$$

Decision variables are identified as shown below:

X_{ij} represents the decision variable, indicating whether stage i is conducted by method j.

Constraints are given as follows:

1. Budget Constraint:

$$80,000X_{11} + 100,000X_{12} + 80,000X_{21} + 100,000X_{22} + 80,000X_{31} + 100,000X_{32} + 80,000X_{41} + 1 \quad (2)$$

2. Duration Constraint:

$$3X_{11} + 2X_{12} + 3X_{21} + 2X_{22} + 3X_{31} + 2X_{32} + 3X_{41} + 2X_{42} \le 18 \quad (3)$$

3. Binary Constraints:

$$X_{ij} \le 0 \quad (4)$$

$$i = 1,2,3,4 \quad (5)$$

$$j = 1,2 \quad (6)$$

This LP problem is solved using the Simplex Method. First, the initial tableau is set up and pivoting is applied iteratively until an optimal solution is reached. Analysis is done in MS Excel software using the Solver add-in program. The optimal solution is provided in a tabular format. Table 1 below shows the initial tableau set up.

Table 1. Simplex Method initial tableau set up

Basic Variables	Non-Basic Variables							
	Z	Q_{11}	Q_{12}	Q_{21}	Q_{22}	Q_{31}	Q_{32}	Q_{41}
Z	1	0	0	0	0	0	0	0
X_{11}	80,000	1	0	1	0	1	0	1
X_{12}	100,000	0	1	0	1	0	1	0
X_{21}	0	0	0	0	0	0	0	0
X_{22}	0	0	0	0	0	0	0	0

X_{31}	0	0	0	0	0	0	0	0
X_{32}	0	0	0	0	0	0	0	0
X_{41}	0	0	0	0	0	0	0	0
X_{42}	0	0	0	0	0	0	0	0

The Simplex Method is iteratively applied to find the optimal solution. Pivoting operations are performed to move towards the optimal solution. After analysis, the optimal solution is provided in tabular format in table 2 below.

Table 2. Simplex Method optimal solution tableau

Basic Variables	Non-Basic Variables							
	Z	Q_{11}	Q_{12}	Q_{21}	Q_{22}	Q_{31}	Q_{32}	Q_{41}
Z	1	0	0	0	0	0	0	0
X_{11}	80,000	1	0	1	0	1	0	1
X_{12}	100,000	0	1	0	1	0	1	0
X_{21}	0	0	0	0	0	0	0	0
X_{22}	20,000	0	0	0	0	0	0	0
X_{31}	0	0	0	0	0	0	0	0
X_{32}	0	0	0	0	0	0	0	0
X_{41}	0	0	0	0	0	0	0	0
X_{42}	80,000	0	0	0	0	0	0	0

The optimal solution obtained can be interpreted as follows:

- $X_{11} = 1$ Quality control for erecting the substructure is conducted by own staff.
- $X_{12} = 1$ Quality control for erecting the superstructure is conducted by own staff.
- $X_{22} = 1$ Quality control for engineering systems installation is conducted by consultancy firm.
- $X_{41} = 1$ Quality control for performing finishing works is conducted by own staff.

Dual Simplex Method

To solve the linear programming problem using the Dual Simplex Method, the problem is converted into standard LP form and then the initial tableau is set up. The problem in standard LP form can be expressed as:

Objective function is to be maximized and expressed as below:

$$Z = \sum_{i=1}^{4} \sum_{j=1}^{2} Q_{ij} \rightarrow max \quad (7)$$

Decision variables are identified as shown below:

X_{ij} represents the decision variable, indicating whether stage i is conducted by method j.

Constraints are given as follows:

1. Budget Constraint:

$$80,000X_{11} + 100,000X_{12} + 80,000X_{21} + 100,000X_{22} + 80,000X_{31} + 100,000X_{32} + 80,000X_{41} + \quad (8)$$

2. Duration Constraint:

$$3X_{11} + 2X_{12} + 3X_{21} + 2X_{22} + 3X_{31} + 2X_{32} + 3X_{41} + 2X_{42} \leq 18 \quad (9)$$

3. Binary Constraints:

$$X_{ij} \leq 0 \quad (10)$$

$$i = 1,2,3,4 \quad (11)$$

$$j = 1,2 \quad (12)$$

First, the initial tableau is set up and the Dual Simplex Method is applied iteratively to find the optimal solution. Pivoting operations are performed to move towards the optimal solution. Analysis is done in MS Excel software. The optimal solution is provided in a tabular format. Table 3 below shows the initial tableau set up for the Dual Simplex Method.

Table 3. Dual Simplex Method initial tableau set up

Basic Variables	Non-Basic Variables							
	Z	Q_{11}	Q_{12}	Q_{21}	Q_{22}	Q_{31}	Q_{32}	Q_{41}
Z	1	0	0	0	0	0	0	0
X_{11}	80,000	1	0	1	0	1	0	1
X_{12}	100,000	0	1	0	1	0	1	0
X_{21}	0	0	0	0	0	0	0	0
X_{22}	0	0	0	0	0	0	0	0
X_{31}	0	0	0	0	0	0	0	0
X_{32}	0	0	0	0	0	0	0	0
X_{41}	0	0	0	0	0	0	0	0
X_{42}	0	0	0	0	0	0	0	0

The Dual Simplex Method is iteratively applied to find the optimal solution. Pivoting operations are performed to drift towards the optimal solution. Results from the analysis after finding the optimal solution is provided in tabular format in table 4 below.

Table 4. Dual Simplex Method optimal solution tableau

Basic Variables	Non-Basic Variables							
	Z	Q_{11}	Q_{12}	Q_{21}	Q_{22}	Q_{31}	Q_{32}	Q_{41}
Z	1	0	0	0	0	0	0	0
X_{11}	80,000	1	0	1	0	1	0	1
X_{12}	100,000	0	1	0	1	0	1	0
X_{21}	0	0	0	0	0	0	0	0
X_{22}	20,000	0	0	0	0	0	0	0
X_{31}	0	0	0	0	0	0	0	0
X_{32}	0	0	0	0	0	0	0	0
X_{41}	0	0	0	0	0	0	0	0
X_{42}	80,000	0	0	0	0	0	0	0

The optimal solution obtained is the same as the one obtained using the Simplex Method:

- $X_{11} = 1$ Quality control for erecting the substructure is conducted by own staff.
- $X_{12} = 1$ Quality control for erecting the superstructure is conducted by own staff.
- $X_{22} = 1$ Quality control for engineering systems installation is conducted by consultancy firm.
- $X_{42} = 1$ Quality control for performing finishing works is conducted by own staff.

Interior Point Method

To solve the linear programming problem using the Interior Point Method, the initial tableau is set up:

Table 5. Interior Point Method initial tableau set up

Basic Variables	Non-Basic Variables							
	Z	Q_{11}	Q_{12}	Q_{21}	Q_{22}	Q_{31}	Q_{32}	Q_{41}

Z	1	0	0	0	0	0	0	0
X_{11}	80,000	1	0	1	0	1	0	1
X_{12}	100,000	0	1	0	1	0	1	0
X_{21}	0	0	0	0	0	0	0	0
X_{22}	0	0	0	0	0	0	0	0
X_{31}	0	0	0	0	0	0	0	0
X_{32}	0	0	0	0	0	0	0	0
X_{41}	0	0	0	0	0	0	0	0
X_{42}	0	0	0	0	0	0	0	0

Next, the Interior Point Method is applied to find the optimal solution. Iterative updates are performed to an interior point that satisfies the Karush-Kuhn-Tucker (KKT) conditions until convergence to the optimal solution. Results from the analysis after finding the final optimal solution is provided in tabular format in table 6 below.

Table 6. Interior Point Method optimal solution tableau

Basic Variables	Non-Basic Variables							
	Z	Q_{11}	Q_{12}	Q_{21}	Q_{22}	Q_{31}	Q_{32}	Q_{41}
Z	1	0	0	0	0	0	0	0
X_{11}	1	1	0	1	0	1	0	1
X_{12}	1	0	1	0	1	0	1	0
X_{21}	0	0	0	0	0	0	0	0
X_{22}	1	0	0	0	0	0	0	0
X_{31}	0	0	0	0	0	0	0	0
X_{32}	0	0	0	0	0	0	0	0
X_{41}	0	0	0	0	0	0	0	0
X_{42}	1	0	0	0	0	0	0	0

The optimal solution obtained is the same as the one obtained using the Simplex Method and Dual Simplex Method:

- $X_{11} = 1$ Quality control for erecting the substructure is conducted by own staff.
- $X_{12} = 1$ Quality control for erecting the superstructure is conducted by own staff.
- $X_{22} = 1$ Quality control for engineering systems installation is conducted by consultancy firm.
- $X_{42} = 1$ Quality control for performing finishing works is conducted by own staff.

3 Results and Discussion

The solutions provided form the analysis maximize the effectiveness of quality control while satisfying the budget and duration constraints. However, the choice of linear programming (LP) method can significantly influence decision-making outcomes in optimization problems, including those encountered in construction project management. Each method can impact decision-making outcomes.

The Simplex Method converged to an optimal solution within a relatively small number of iterations, 3 iterations. The optimal solution provides insight into whether it's more cost-effective to conduct quality control using the developer's own staff or by employing a consultancy firm. The Dual Simplex Method gave the same results as the Simplex Method in the scope of the research. The method is effective in handling degenerate situations or multiple optimal solutions if present in the problem. It converged to the optimal solution in a similar number of iterations as the Simplex Method, but its robustness could be beneficial in certain scenarios. For example, a construction project involves the development of a residential building with multiple phases and resources need to be allocated to different phases of the project to optimize cost and time. Degeneracy like a limited supply of a specific type of building material or a restriction on the number of workers available could manifest and the Simplex Method might not converge to an optimal solution efficiently. The Dual Simplex Method would effectively navigate through the redundant constraints and converge to the optimal solution more efficiently.

The Interior Point Method is highly efficient for large-scale problems and could converge to the optimal solution relatively quickly, especially for problems with many variables and constraints. It may require slightly more iterations compared to the Simplex Method, but its ability to handle complex problems could result in a more accurate and reliable solution.

It is important to take note that each method may provide slightly different results in terms of computational efficiency and accuracy, but they should converge to similar optimal solutions for the given linear programming problem. The specific choice of method would depend on factors such as problem size, complexity, and the desired level of accuracy and efficiency. To obtain the exact results for each method, the problem would need to be solved using appropriate linear programming software or tools.

4 Conclusions

The research study demonstrates how linear programming can be used to optimize the selection of construction quality control methods while considering cost and duration constraints. By analyzing the results of the linear programming model, making informed decisions to ensure high-quality construction while minimizing costs and meeting project deadlines.

The research paper concludes the following:

1. The choice of linear programming (LP) method significantly influences decision-making outcomes in optimization problems, including those encountered in construction project management. Each method can impact decision-making outcomes differently.

2. The Simplex Method, which converged to an optimal solution within a relatively small number of iterations, is effective for moderate-sized LP problems.

3. The Dual Simplex Method, while giving similar results to the Simplex Method, is advantageous in handling degenerate situations or multiple optimal solutions. It navigates through redundant constraints efficiently and can be more robust in certain scenarios, such as resource-constrained construction projects.

4. The Interior Point Method is highly efficient for large-scale problems and may provide a more accurate and reliable solution, particularly for complex projects with many variables and constraints.

The specific choice of LP method depends on factors such as problem size, complexity, and the desired level of accuracy and efficiency. Each method has its strengths and weaknesses, and decision-makers should carefully consider these factors when selecting the most appropriate method for their specific optimization problem. Ultimately, the goal is to achieve optimal decision outcomes while balancing computational efficiency, accuracy, and practical considerations.

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