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OPTIMIZATION OF REBAR CUTTING PLANS USING MULTIPLE STOCK LENGTHS AND INTEGER LINEAR PROGRAMMING: A CASE STUDY OF A WASTEWATER TREATMENT PLANT

Sarayut Malai[1] , Lamay Junthakhao[2*], Thiranan Sonkaew[2], Donrudee Sookjai[2] , Haruthai Thaisuchat[2] and Pincha Torkittikul[1]
[1]Faculty of Industrial Technology, Lampang Rajabhat University
[2]Faculty of Science, Lampang Rajabhat University
*Corresponding author : lamay@lpru.ac.th

ABSTRACT

This research aims to develop and evaluate the efficiency of rebar cutting plans for wastewater treatment plant construction, employing Integer Linear Programming (ILP) to minimize scrap waste and overall costs. The study compares cutting plans for rebar sizes DB12, DB16, and DB25 mm, utilizing standard stock lengths of 10 meters, 12 meters, and a combination of both. Rebar requirements were derived from the structural design specifications of a wastewater treatment plant case study. The findings demonstrate that combining 10 meter and 12 meter stock lengths yields the highest efficiency across all rebar sizes. Notably, for DB25 rebar, this approach reduced scrap waste from 17.09 %, when using only 12 meter stock, to a mere 1.95 %, while increasing material utilization to 98.05 % and remaining robust under moderate increases in rebar demand. Furthermore, it achieved material cost savings of up to 15.44 % and reduced greenhouse gas emissions by 15.45 % compared to using 12 meter stock alone. These results underscore that meticulous cutting plan optimization, incorporating multiple stock lengths and ILP, is a pivotal strategy for waste reduction, cost efficiency, and promoting sustainability in the construction industry.

Keywords: Rebar Cutting, Integer Linear Programming, Multiple Stock Lengths, Scrap Waste, Wastewater Treatment

บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อพัฒนาและประเมินประสิทธิภาพของแผนการตัดเหล็กเสริมสำหรับการก่อสร้างโรงบำบัดน้ำเสีย โดยประยุกต์ใช้การกำหนดการเชิงเส้นจำนวนเต็ม (Integer Linear Programming: ILP) เพื่อลดปริมาณเศษวัสดุเหลือทิ้งและต้นทุนรวม การศึกษานี้เปรียบเทียบแผนการตัดเหล็กสำหรับเหล็กเส้นข้ออ้อยขนาดเส้นผ่านศูนย์กลาง 12, 16 และ 25 มิลลิเมตร (DB12, DB16 และ DB25) โดยพิจารณาความยาวเหล็กมาตรฐาน 3 กรณี ได้แก่ ความยาว 10 เมตร 12 เมตร และการใช้ความยาวผสมกันทั้งสองขนาด ข้อมูลความต้องการเหล็กเสริมอ้างอิงจากแบบก่อสร้างโครงสร้างของกรณีศึกษาโรงบำบัดน้ำเสีย ผล

การศึกษาแสดงให้เห็นว่าการใช้ความยาวเหล็กมาตรฐานผสมกันทั้ง 10 เมตรและ 12 เมตร ให้ประสิทธิภาพสูงสุดในทุกขนาดหน้าตัดเหล็ก โดยเฉพาะอย่างยิ่งสำหรับเหล็ก DB25 แนวทางนี้สามารถลดปริมาณเศษวัสดุเหลือทิ้งจากร้อยละ 17.09 เมื่อเปรียบเทียบด้วยใช้ความยาว 12 เมตรเพียงอย่างเดียว เหลือเพียงร้อยละ 1.95 เพิ่มอัตราการใช้ประโยชน์วัสดุเป็นร้อยละ 98.05 ซึ่งการคำนวณด้วย ILP นี้มีความเสถียรภายใต้การเพิ่มขึ้นของความต้องการเหล็ก นอกจากนี้ยังสามารถประหยัดต้นทุนค่าวัสดุได้ถึงร้อยละ 15.44 และลดการปล่อยก๊าซเรือนกระจกลงร้อยละ 15.45 ผลลัพธ์เหล่านี้ชี้ให้เห็นว่าการเพิ่มประสิทธิภาพแผนการตัดเหล็กอย่างละเอียดโดยพิจารณาใช้ความยาวมาตรฐานหลายขนาดร่วมกับ ILP เป็นกลยุทธ์สำคัญในการลดของเสีย เพิ่มความคุ้มค่าด้านต้นทุน และส่งเสริมความยั่งยืนในอุตสาหกรรมก่อสร้าง

คำสำคัญ: การตัดเหล็กเสริม, การกำหนดการเชิงเส้นจำนวนเต็ม, ความยาวเหล็กมาตรฐานหลายขนาด, เศษวัสดุเหลือทิ้ง, การบำบัดน้ำเสีย

1. Introduction

The construction industry serves as a cornerstone for economic development and infrastructure advancement, particularly in public utility projects such as wastewater treatment plants, which are vital for sustainable water resource management. Nevertheless, achieving optimal utilization of construction materials remains a significant challenge, especially for reinforced concrete rebar, a critical component in reinforced concrete structures. Cutting rebar from standard stock lengths, such as 10 or 12 meters, often results in scrap waste that cannot be reused or usable leftovers, leading to increased material costs and environmental impacts due to inefficient resource use. Scrap waste from rebar cutting arises from multiple factors, including mismatches between standard stock lengths and required cut lengths, inefficient cutting plans, and technical limitations of cutting equipment. Research by Luangcharoenrat et al. [1] highlights key contributors to construction waste in Thailand, such as design changes, improper material storage, and lack of worker expertise. Consequently, integrating Bar Bending Schedules (BBS), Bar Cut Lists (BCL), and Cutting Plans is essential for enhancing resource efficiency. To address these challenges, prior studies have employed operations research techniques, such as Linear Programming and Integer Linear Programming (ILP), to minimize waste and costs. For instance, Memon et al. [2] proposed strategies for waste reduction through efficient material planning, effective on-site material management, and workforce skill development. Furthermore, reducing construction waste yields significant environmental benefits. According to the UK Green Building Council [3], steel production impacts ecosystems through mining, substantial water consumption, and contamination of water and soil. Adopting Circular Economy principles and the 3R framework (Reduce, Reuse, Recycle), as advocated by Nwachukwu et al. [4], is thus a critical strategy for mitigating these impacts. While national reports highlight the urgency of circular resource strategies amidst rapid urbanization [5], practical implementation remains in early stages. Specifically regarding rebar, several Thai studies have demonstrated that optimizing Bar Bending Schedules (BBS) and Bar Cut Lists (BCL) can substantially reduce trim loss [6, 7]. Recent studies have further advanced this by applying computational techniques, such as Particle Swarm Optimization (PSO), to minimize scrap in high-rise building columns [8].

Life Cycle Assessment (LCA) serves as a robust tool for evaluating the environmental impacts of construction materials across their lifecycle. Reducing rebar cutting waste aligns with upstream optimization strategies, which curtail raw material use and greenhouse gas emissions from the production phase, supporting the Sustainable Development Goals (SDGs), particularly SDG 12 on sustainable production and consumption [9-12]. Despite advancements in cutting optimization technologies, their application in Thailand, particularly for specialized projects like wastewater treatment plants, remains limited. Kareem et al. [13] noted that waste management in construction often receives low priority and lacks incentives.

However, existing literature presents two significant gaps. First, most studies focus on single-building projects using a single standard stock length, rarely evaluating multiple stock-length combinations (e.g., 10 m and 12 m) to optimize material utilization. Second, while the carbon footprint of steel production in Thailand is significant, this study explicitly quantifies the environmental benefits (GHG reduction) associated with optimized cutting plans. Therefore, this research aims to develop and compare rebar cutting plans for rebar sizes DB12, DB16, and DB25 mm in wastewater treatment plant construction, considering standard stock lengths of 10 meters, 12 meters, and a combination of both, using ILP to identify plans that minimize waste.

The anticipated outcomes of this study will provide practical guidelines for civil engineers and contractors to reduce material costs, mitigate environmental impacts, and promote sustainable resource use in Thailand's construction industry. This research also addresses the challenge of balancing the complexity of cutting plans with practical implementation, aligning with the emphasis by Sagan and Mach [14] and Kumawat et al. [15] on the economic, social, and environmental dimensions of construction waste management.

2. Methodology

This research aims to develop and optimize rebar cutting plans for wastewater treatment plant construction using Integer Linear Programming (ILP) to minimize scrap waste and total costs. The methodology comprises five key steps, outlined as follows:

2.1 Data Collection and Bar Bending Schedule (BBS) Preparation

The initial step involved a thorough review of the detailed structural drawings of the wastewater treatment plant and the project's technical specifications to identify the type (Figure 1), diameter (DB12, DB16, and DB25 mm), and quantity of rebar required for each structural component. Subsequently, the required cutting lengths for each rebar item were calculated, accounting for bending, hook allowances, and lap splice lengths following structural design standards. All data were compiled into a Bar Bending Schedule (BBS), which included critical details such as rebar identification numbers, type and size, quantity, cutting length per piece, bending shape codes, installation locations, and total weight for each rebar type. This document served as a foundational resource for planning subsequent cutting operations.

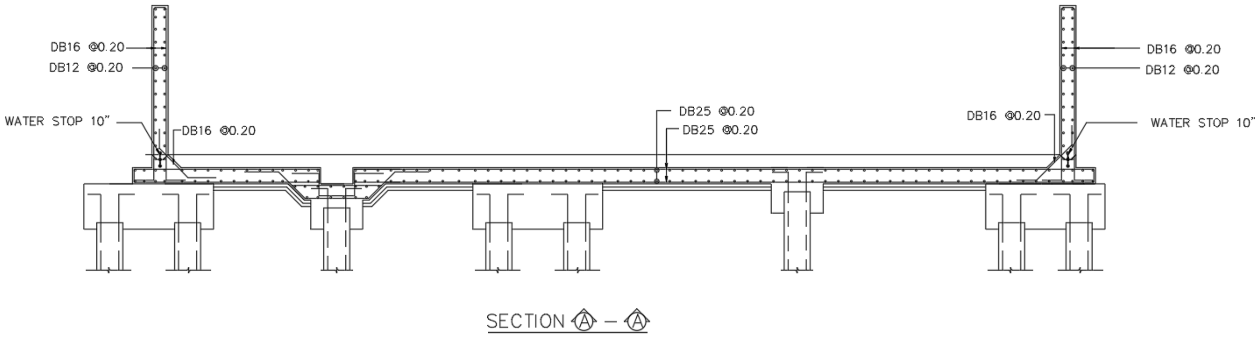

Figure 1 Example cross-sectional view of a reinforced concrete wastewater treatment tank

2.2 Bar Cut List (BCL) Development

To ensure precision and alignment with project requirements, data from the BBS were extracted and organized into a BCL, categorized by rebar diameter (DB12, DB16, and DB25). Cutting lengths that were identical or similar were grouped to streamline the cutting process, and the total quantity required for each cutting length was specified. This step facilitated the development of efficient cutting plans by providing a clear and consolidated dataset for further analysis.

2.3 Data Preparation for Stock Length Scenarios

This phase focuses on preparing essential fundamental data for analysis. This is achieved by calculating the Total Required Length for each rebar size, specifically DB12, DB16, and DB25. These calculations consider three standard rebar length options: 10 meters, 12 meters, and a combination of both. The total length is derived by summing all cutting lengths as in the BCL, which is extracted from the BBS.

During this total length calculation, significant constraints are considered. For instance, if certain rebar items exceed 10 meters in length, they must be cut into two pieces, necessitating the addition of a lap splice. This lap splice is specified to be no less than 40 times the rebar diameter. While the Department of Public Works and Town & Country Planning's (DPT 1103-64) Standard for Concrete Reinforcement Work stipulates a minimum lap splice length of 36 times the rebar diameter for SD 40 deformed bars [16], the 40 times diameter criterion is adopted in this study, which, in some cases, leads to an increase in the total required length. The compiled data, including the total required length and the number of distinct cutting lengths (Constraints), are summarized in Table 1.

As observed from Table 1, the total required length for DB 12 and DB 16 rebar is higher when using the 10-meter standard rebar length compared to the 12-meter standard or the combined length option. This is primarily due to the actual required length of some rebar items exceeding 10 meters, which necessitates cutting them into two pieces and subsequently lap splicing them. An additional length is required for the lap splice, specified to be no less than 40 times the rebar diameter. For example, if a DB16 rebar requires a length of 11.25 meters and a 10-meter stock length is used, it must be cut into a 10-meter piece and a 1.25-meter piece. Adding the lap splice (40 × 0.016 meters) increases the total length to be cut from stock to 11.89 meters, which is greater than the original required length. This phenomenon leads to a higher Total Required Length for the 10-meter standard rebar option for DB12 and DB16 deformed bars. In contrast, for DB 25 deformed bars, the Total Required Length remains constant across all options, as all cutting lengths in this case study do not exceed 10 meters, thus eliminating the need for lap splices.

Table 1 Total Required Length and Number of Different Cutting Lengths (Constraints) for Various Rebar Sizes under Standard Rebar Length Options

Size	**Standard Length 10 m (Total Required Length / Constraints)**	**Standard Length 12 m (Total Required Length / Constraints)**	**Standard Length Combine 10 and 12 m (Total Required Length / Constraints)**
DB 12	729.30 m/ 8 Constraints	726.42 m/ 7 Constraints	726.42 m/ 7 Constraints
DB 16	8,140.98 m/ 10 Constraints	8,018.10 m/ 10 Constraints	8,018.10 m/ 10 Constraints
DB 25	9,362.12 m/ 4 Constraints	9,362.12 m/ 4 Constraints	9,362.12 m/ 4 Constraints

The data concerning the total required rebar length and the number of different cutting lengths, specifically the Cutting Length List for 16 mm diameter deformed bars, for calculating rebar cutting results using Integer Linear Programming for two options: (1) using 12-meter standard rebar length and (2) using a combination of 10-meter and 12-meter standard lengths, are presented in Table 2 and Figure 2. This information will serve as fundamental input for generating cutting patterns and determining the optimal cutting plan using integer programming in the subsequent steps. This method of data preparation ensures that the evaluation of each standard length option is rational and aligns with practical construction practices.

2.4 Cutting Pattern Generation

Following the preparation of the Bar Cut List for each case study, based on rebar diameter and length constraints, the subsequent step involves generating a set of all possible cutting patterns for each standard rebar length (10 meters or 12 meters). Each cutting pattern specifies how one standard rebar length is to be cut to obtain the required sub-pieces according to the Bar Cut List. The conditions are that the total length of all sub-pieces within each pattern must not exceed the standard rebar length, and the number of cut pieces must be positive integers. The generation of these diverse and comprehensive cutting patterns serves as critical input for calculations using the integer linear programming model.

As an illustration, the generation of cutting patterns for DB 16 deformed bars using 12-meter rebar lengths is presented in Figure 3. Eight example cutting patterns (X1 to X8) are shown, each corresponding to a possible way of cutting the 12-meter DB 16 rebar. Each pattern is subdivided into the required lengths and any remaining (scrap) portions. For instance, X1 utilizes the full 12 meters of rebar with no remainder, indicating optimal resource utilization. Conversely, other patterns, such as X2, X3, X4, X5, X6, X7, and X8, show varying amounts of remainder, indicating potential material waste from the cutting process.

Table 2 Cutting Length List for DB16 Rebar for Integer Linear Programming Calculation Results for 2 Options: 1) Using 12-meter Standard Rebar Length and 2) Using a Combination of 10-meter and 12-meter Standard Lengths

No.	Rebar Diameter (mm)	Quantity (pieces))	Length per piece (m)	Total Length (m)	Cutting Pattern
1	DB16	144	12.000	1,728.000	12.000
2		48	11.250	540.000	11.250
3		270	10.000	2,700.000	0.200 | 9.800
4		174	8.950	1,557.300	0.200 | 8.750
5		24	7.950	190.800	0.100 | 7.850
6		48	6.000	288.000	6.000
7		48	5.850	280.800	5.850
8		24	5.000	120.000	0.100 | 4.900
9		36	1.700	61.200	0.100 | 1.500 | 0.100
10		368	1.500	552.000	0.200 | 1.000 | 0.200
Total Length (m)				8,018.100	
The weight of a DB 16 mm (kg/m)				1.578	
Total Rebar Weight (kg)				12,652.562	

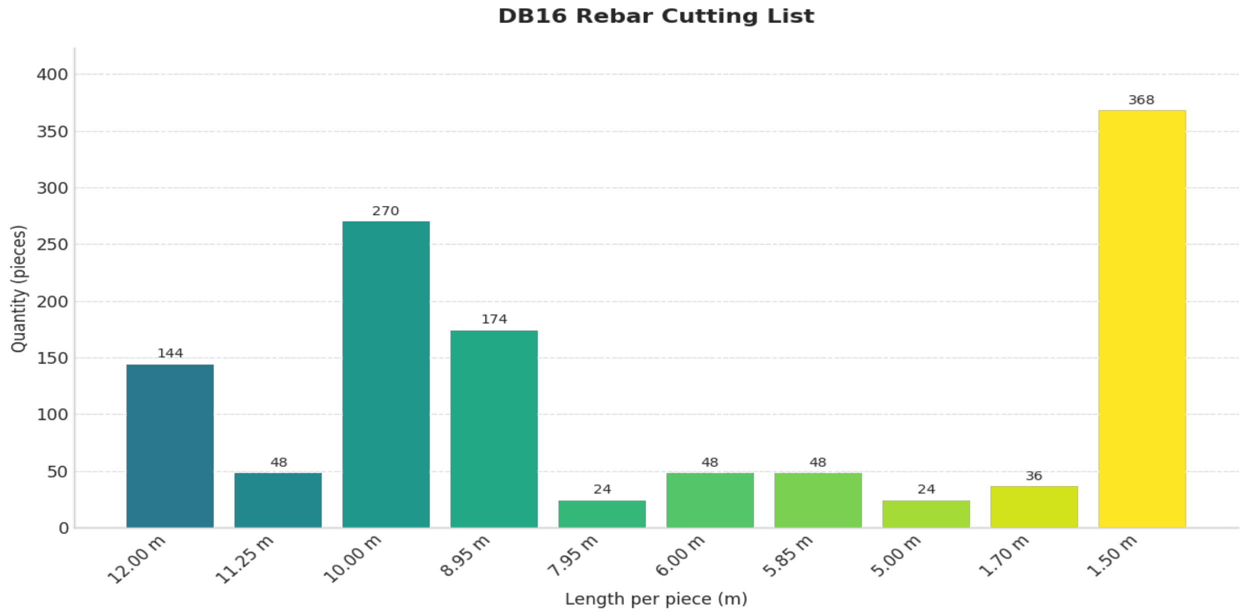

Figure 2 Quantity of DB 16 Rebar Required for Integer Linear Programming Calculation Results for 2 Options: 1) Using 12 meter Standard Rebar Length and 2) Using a Combination of 10 meter and 12 meter Standard Lengths

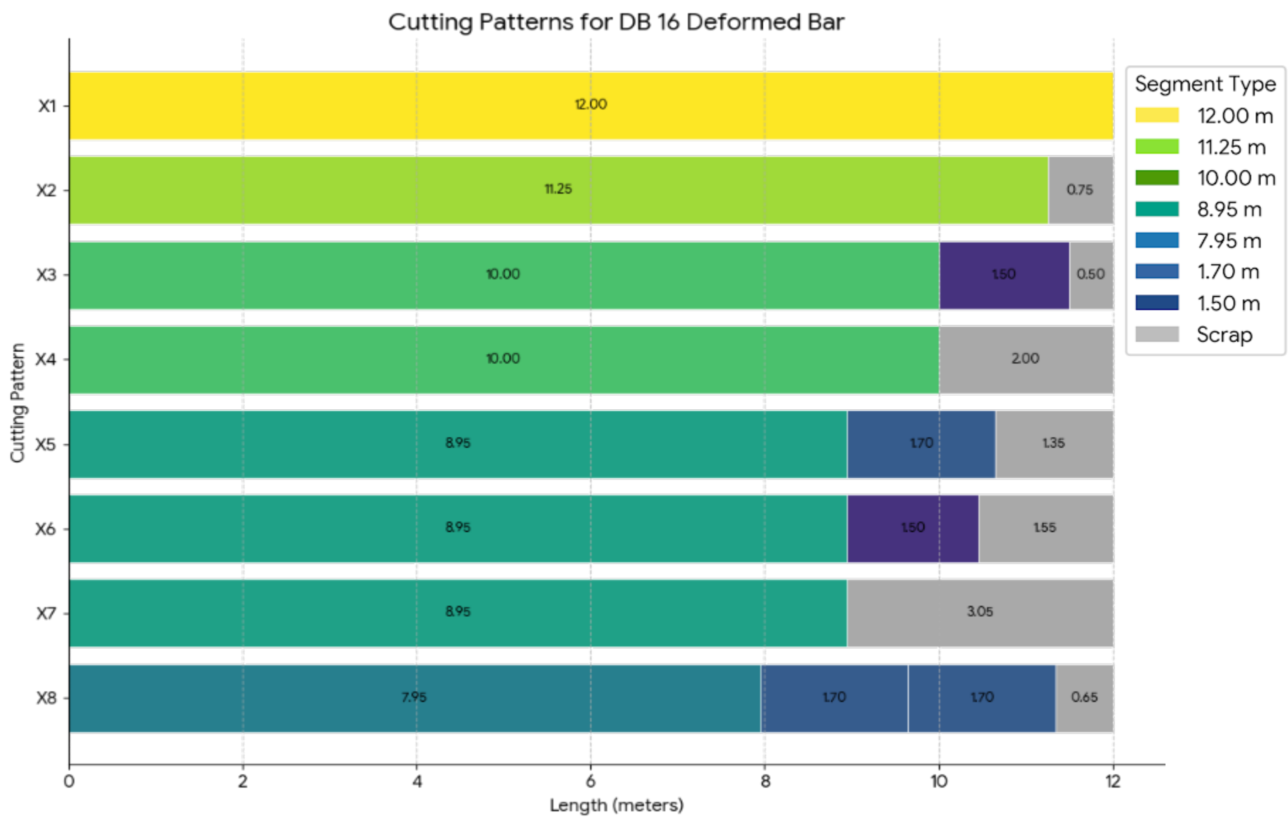

Figure 3 Example Cutting Patterns for DB 16 Deformed Bar, 12 Meters in Length: Analysis of Utilization and Remainder (X1-X8)

2.5 Optimal Cutting Plan Determination using Integer Linear Programming and Data Analysis

To identify cutting plans that minimize scrap waste and maximize yield, this study employed an Integer Linear Programming (ILP) mathematical model, from WinQSB version 2.0 program comprising the following key components: Objective Function

1) Objective Function

$$\text{Minimize} \quad Z = \sum_{i=1}^{n} C_i \boldsymbol{X_i} \tag{1}$$

Where:

Z : Total cost or total standard rebar quantity used (cost unit depending on C_i), which is the value to be minimized to reduce waste and material cost.

X_i : Number of times cutting pattern i is selected (non-negative integer).

C_i : Cost associated with using cutting pattern i once.

2) Subject to Constraints

2.1) Demand constraints

$$\text{Subject to} \quad \sum_{i=1}^{n} p_{ij} \boldsymbol{X_i} \geq \boldsymbol{d_j} \qquad \forall_{\boldsymbol{j}} \in \{\boldsymbol{1}, \ldots, \boldsymbol{s}\} \tag{2}$$

Where:

p_{ij} : Number of pieces of type j (length lj) obtained from using cutting pattern i once (non-negative integer).

d_j : Total number of pieces of type j (length lj) required according to the Bar Cut List (Unit: pieces).

2.2) Production Capacity Constraint

$$\sum_{j=1}^{s} p_{ij} \boldsymbol{l_j} \leq \boldsymbol{L_i} \qquad \forall_{\boldsymbol{i}} \in \{\boldsymbol{1}, \ldots, \boldsymbol{n}\} \tag{3}$$

Where:

l_j : Length of one piece of type j (Unit: meters).

L_i : Length of the standard rebar used in cutting pattern i (Unit: meters).

2.3) Non-negativity and Integrality constraint :

$$X_i \geq 0, X_i \in Z \qquad \forall_i$$
$$p_{ij} \geq 0, p_{ij} \in Z \qquad \forall_{i,j}$$

The ILP model was applied to compute the most optimal cutting plans, prioritizing material efficiency and minimal waste generation. Upon completing the ILP computations for each case study and stock length scenario, the final step involved analyzing the results based on predefined performance metrics, including the amount of cutting waste (scrap and excess, if distinguished), total material usage (number of stock bars and total length), and yield, calculated as the ratio of the total required length to the total stock length used. The analysis encompassed a comparison of waste quantities and yield across the three stock length scenarios for each rebar size to determine the most efficient cutting strategy. Additionally, reductions in material costs, sensitivity and greenhouse gas emissions from production were evaluated to highlight the economic and environmental benefits. The flowchart of the research methodology employed in this study is shown in Figure 4.

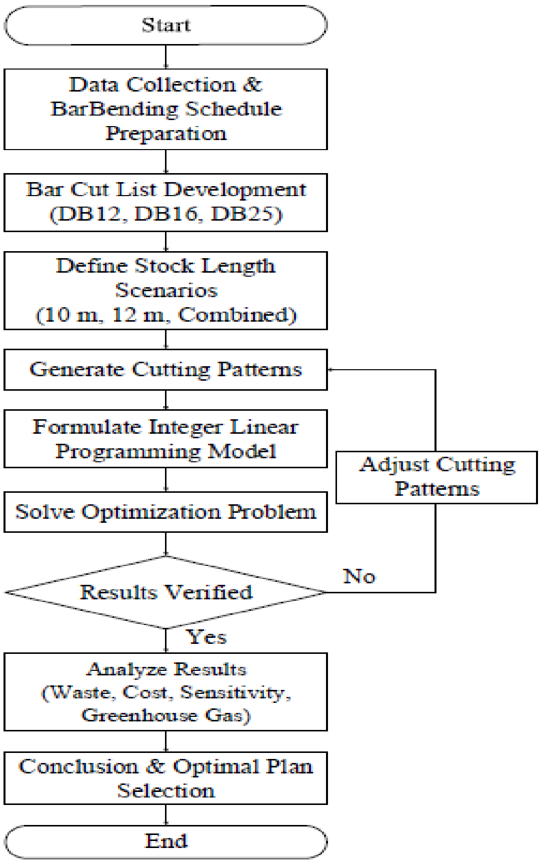

Figure 4 Flowchart illustrating the research methodology, including data collection, ILP model formulation, optimization, and analysis

3. Results

This research evaluates the efficiency of rebar cutting plans for wastewater treatment plant construction using Integer Linear Programming (ILP). The analysis compares the use of 10-meter, 12-meter, and combined stock lengths, revealing significant differences in material usage, waste, costs, and environmental impacts. The findings are presented in five subsections:

3.1 Comparison of Cutting Patterns and Rebar Utilization Efficiency

The analysis of rebar cutting patterns using the ILP model highlights distinct differences in the number of rebar stock used and cutting efficiency across different standard stock lengths (Table 3). For DB12 rebar, using 12-meter stock required 66 bars with 8 cutting patterns, while 10-meter stock necessitated 79 bars with 6 patterns. However, combining both stock lengths reduced usage to 66 bars (45 bars of 12 meters and 21 bars of 10 meters) with 7 cutting patterns, indicating improved efficiency.

For DB16 rebar, the 12-meter stock scenario required 720 bars with 10 cutting patterns, whereas the 10-meter stock demanded 840 bars with 19 patterns. The combined stock length approach reduced the total to 768 bars (287 bars of 12 meters and 481 bars of 10 meters) with 14 cutting patterns, demonstrating more effective resource management.

In the case of DB25 rebar, the 12-meter stock required 941 bars, and the 10-meter stock needed 1,010 bars. Combining both lengths resulted in 941 bars (69 bars of 12 meters and 872 bars of 10 meters), with all scenarios utilizing 4 cutting patterns. These findings suggest that the combined stock length approach optimizes resource use, particularly for larger rebar sizes.

Table 3 Cutting Patterns and Rebar Quantities Used Under Various Standard Length Options

Rebar Diameter (mm)	Stock Length Option	Total Required Length (m)	No. of Constraint	No. of Variable	Number of Layout or Pattern	No. of Rebar Bars (pcs)
DB 12	12 m	726.42	7	40	8	66
	10 m	729.30	7	78	6	79
	Combined (12 & 10 m)	726.42	7	40 (12 m), 25 (10 m)	5 (12 m), 2 (10 m)	45 (12 m), 21 (10 m)
DB 16	12 m	8,018.10	10	79	10	720
	10 m	8,140.98	10	129	19	840
	Combined (12 & 10 m)	8,018.10	10	79 (12 m), 50 (10 m)	8 (12 m), 6 (10 m)	287 (12 m), 481 (10 m)
DB 25	12 m	9,362.12	4	10	4	941
	10 m	9,362.12	4	18	4	1,010
	Combined (12 & 10 m)	9,362.12	4	10 (12 m), 8 (10 m)	1 (12 m), 3 (10 m)	69 (12 m), 872 (10 m)

3.2 Analysis of Waste Generation and Material Utilization Efficiency

Material utilization efficiency is a critical indicator of the success of rebar cutting plans. The analysis revealed significant differences in Material Utilization Rate and Scrap Waste across stock length scenarios (Table 4). For DB12 rebar, combining 10-meter and 12 meter stock achieved a utilization rate of 96.86 %, surpassing the 91.72 % for 12-meter stock alone and outperforming the 10-meter stock scenario. This resulted in waste of only 23.58 meters, or 3.14 % of the total stock length used.

For DB16 rebar, the combined stock length approach yielded a utilization rate of 97.14 %, compared to 92.80 % for 12-meter stock and higher than the 10 meter stock. Waste was reduced to 235.9 meters, or 2.86 %, reflecting more cost-effective material management.

For DB25 rebar, the combined stock length scenario excelled with a utilization rate of 98.05 %, significantly higher than the 82.91 % for 12-meter stock and the 10-meter stock. Waste decreased from 1,929.88 meters (12-meter stock) to just 185.88 meters, a reduction of 90.37 %. These results confirm the superior efficiency of the combined stock length approach in minimizing waste.

Table 4 Comparison of Material Utilization Rate and Rebar Cutting Waste Volume

Rebar Diameter (mm)	Stock Length Option	Total Required Length (m)	Total Stock Length Used (m)	Material Utilization Rate (%)	Excess Material (m)	Scrap Waste Material (m)	Scrap Waste Percentage (%)
DB 12	12 m	726.42	792.00	91.72	0	65.58	8.28
	10 m	729.30	790.00	92.32	0	20.93	2.65
	Combined (12 & 10 m)	726.42	750.00	96.86	0	23.58	3.14
DB 16	12 m	8,018.10	8,640.00	92.80	0	621.90	7.20
	10 m	8,140.98	8,400.00	96.92	0	259.02	3.08
	Combined (12 & 10 m)	8,018.10	8,254.00	97.14	0	235.90	2.86
DB 25	12 m	9,362.12	11,292.00	82.91	0	1,929.88	17.09
	10 m	9,362.12	10,100.00	92.69	0	737.88	7.31
	Combined (12 & 10 m)	9,362.12	9,548.00	98.05	0	185.88	1.95

3.3 Analysis of Economic Impacts and Cost-Effectiveness

The economic analysis demonstrated notable cost savings across stock length scenarios, calculated based on the total rebar weight and current market price (20 THB per kilogram). For DB12 rebar, the combined stock length approach resulted in a material cost of 12,901.20 THB, saving 1,164.60 THB (8.28 %) compared to the 12-meter stock alone. Waste-related costs dropped from 418.78-1,164.70 THB, underscoring enhanced economic viability.

For DB16 rebar, the combined approach yielded a material cost of 260,496.20 THB, saving 12,182.20 THB (4.47 %) relative to the 12 meter stock. Waste costs decreased from 7,445.00 - 19,627.16 THB, reflecting efficient resource utilization.

For DB25 rebar, the combined stock length scenario achieved a material cost of 735,768.80 THB, saving 134,392.60 THB (15.44 %) compared to the 12-meter stock. Waste costs plummeted from 14,323.91 - 148,716.55 THB, (90.37 % reduction), highlighting the substantial economic benefits of the combined approach.

Table 5 Comparison of Material Costs and Economic Savings from Rebar Cutting Plans

Rebar Diameter (mm)	Stock Length Option	Total Weight (kg)	Material Cost (THB)	Waste Cost (THB)	Cost Savings vs. 12 m (THB)	Cost Savings (%)
DB 12	12 m	703.29	14,065.80	1,164.70	-	-
	10 m	701.52	14,030.40	371.71	35.40	0.25
	Combined (12 & 10 m)	645.06	12,901.20	418.78	1,164.60	8.28
DB 16	12 m	13,633.92	272,678.40	19,627.16	-	-
	10 m	13,255.20	265,104.00	8,174.67	7,574.40	2.78
	Combined (12 & 10 m)	13,024.81	260,496.20	7,445.00	12,182.20	4.47
DB 25	12 m	43,508.07	870,161.40	148,716.55	-	-
	10 m	38,915.30	778,306.00	56,861.03	91,855.40	10.56
	Combined (12 & 10 m)	36,788.44	735,768.80	14,323.91	134,392.60	15.44

Note: Material cost calculated based on current market rates: of 20.00 THB/kg

3.4 Sensitivity Analysis Results

To examine the robustness of the proposed ILP model, a sensitivity analysis was conducted by increasing the demand for rebar by approximately 5–8%. The resulting required cutting quantities for the combined 10 and 12 m rebar are presented in Table 6. The analysis results for the combined steel lengths (10 m & 12 m) of DB12, DB16, and DB25 indicate that, although material usage and total cost fluctuate in response to demand variations, the scrap waste percentage remains highly stable, with changes limited to only ±0.1–0.2%. Importantly, the efficiency ranking of the alternatives remains unchanged. The combined length option consistently yields the lowest scrap waste percentage across all demand scenarios.

Table 6. Results of the sensitivity analysis for DB12, DB16, and DB25 rebar using combined 10 m and 12 m lengths under a 5-8% increase in demand.

Rebar Size	Demand Scenario	Total Stock (m)	Scrap Waste (m)	Scrap Waste (%)	Material Cost (THB)
DB 12	Base Case	750.00	23.580	3.14	57,795.00
Combined (10 & 12 m)	Demand +8.228%	812.00	25.810	3.18	62,572.702
DB 16	Base Case	8,254.00	235.90	2.86	636,053.20
Combined (10 & 12 m)	Demand + 5.533 %	8,712.00	250.25	2.87	671,346.72
DB 25	Base Case	9,548.00	185.8	1.95	735,768.88
Combined (10 & 12 m)	Demand +5.048%	10,034.00	199.28	1.99	773,220.04

3.5 Assessment of Environmental Impacts and Greenhouse Gas Emissions

Environmental considerations are integrated to modern construction practices. This study assessed greenhouse gas emissions from rebar cutting, using a standard carbon emission factor of 0.8 $kgCO_2eq$ per 1.0 kg of steel production [17]. The results are show in Table 7. For DB12 rebar, the combined stock length approach reduced total greenhouse gas emissions to 516.05 $kgCO_2eq$, an 8.29% decrease compared to 562.64 $kgCO_2eq$ for 12 meter stock and 561.22 $kgCO_2eq$ for 10 only meter stock. This reduction stemmed primarily from lower waste, with emissions from waste dropping from 46.59 $kgCO_2eq$ (12 meters) and 14.87 $kgCO_2eq$ (10 meters) to 16.76 $kgCO_2eq$ (combination).

For DB16 rebar, the combined approach lowered total emissions to 10,419.85 $kgCO_2eq$, a 4.47% reduction compared to the 12-meter stock. Waste-related emissions decreased from 785.09 $kgCO_2eq$ (12 meters) and 326.99 $kgCO_2eq$ (10 meters) to 297.81 $kgCO_2eq$ (combination), indicating a significant environmental benefit.

For DB25 rebar, the combined stock length scenario yielded the most pronounced results, reducing total emissions to 29,430.76 $kgCO_2eq$, a 15.45% decrease from 34,806.46 $kgCO_2eq$ for 12 meter stock, equivalent to a 5,375.70 $kgCO_2eq$ reduction. Waste-related emissions fell dramatically from 5,948.67 $kgCO_2eq$ (12 meters) and 2,274.45 $kgCO_2eq$ (10 meters) to 572.96 $kgCO_2eq$. These findings emphasize the environmental advantages of optimized cutting plans.

Table 7 Comparison of Greenhouse Gas Emissions from Each Rebar Cutting Plan.

Rebar Diameter (mm)	Stock Length Option	Total Weight (kg)	Carbon Emissions (kg CO_2eq)	Emissions from Waste (kg CO_2eq)	Emissions Reductions Only vs. 12 m (kg CO_2eq)	Emissions Reduction (%)
DB 12	12 m	703.29	562.64	46.59	0.00	0
	10 m	701.52	561.22	14.87	1.42	0.26
	Combined (12 & 10 m)	645.06	516.05	16.76	46.59	8.29
DB 16	12 m	13,633.92	10,907.14	785.09	0.00	0
	10 m	13,255.20	10,604.16	326.99	302.98	2.78
	Combined (12 & 10 m)	13,024.81	10,419.85	297.81	487.29	4.47
DB 25	12 m	43,508.07	34,806.46	5,948.67	0.00	0
	10 m	38,915.30	31,132.24	2,274.45	3,674.22	10.56
	Combined (12 & 10 m)	36,788.44	29,430.76	572.96	5,375.70	15.45

Note: Carbon emissions calculated based on 0.8 kgCO_2 per 1.0 kg of steel rebar production (industry standard emission factor) Thailand Greenhouse Gas Management Organization [17]

4. Discussions

The findings of this research demonstrate the exceptional efficacy of employing Integer Linear Programming (ILP) alongside the use of multiple standard stock lengths in reducing waste, material costs, and environmental impacts in wastewater treatment plant construction. These results comprehensively address the research objectives and strengthen existing knowledge on material management and waste reduction in the construction industry.

The significant reduction in waste, particularly for DB25 rebar, from 17.09 % to just 1.95%, reflects the increased flexibility afforded by combining stock lengths, enabling more optimal arrangement of required cutting lengths. This aligns with the principles of the Cutting Stock Problem (CSP), which posit that greater variety in input material sizes enhances the potential to minimize trim loss. The ability of the combined 10-meter and 12-meter stock approach to achieve waste levels comparable to custom-length rebar, without necessitating changes in procurement processes, presents a practical and cost-effective solution for contractors.

The success of ILP in this study corroborates prior research utilizing mathematical programming to address CSP, such as Thaweethamsatit et al. [8], who employed Particle Swarm Optimization (PSO) to reduce waste from 13.86 % to 2.88 %, and Rácz [18], who developed an MILP model for one-dimensional CSP. The results further emphasize the importance of flexibility in cutting processes, particularly when certain cutting lengths slightly exceed 10 meters. The availability of 12-meter stock reduces the need for lap splices, thereby decreasing total material usage and associated waste.

Moreover, the calculated reductions in material costs and greenhouse gas emissions reinforce the concept of sustainable construction. The 15.45% carbon reduction for DB25 rebar aligns with recommendations by UK Green Building Council [3] and Sagan and Mach [14], who advocate for addressing economic, social, and environmental dimensions in construction waste management. The application of the 3R principles (Reduce, Reuse, Recycle), as proposed by Nwachukwu et al. [4] and Kumawat et al. [15], is validated through the demonstrated reductions in raw material use and environmental impact.

Nevertheless, this study has certain limitations. First, it is confined to the case study of a wastewater treatment plant and rebar sizes DB12, DB16, and DB25, necessitating further testing in diverse project contexts. Second, while the ILP model yields optimal results, its widespread adoption may require specialized expertise or software, posing challenges for smaller contractors. Additionally, cost and environmental impact calculations are based on current steel prices and carbon emission factors, which may fluctuate over time.

The findings also hold significant potential for integration with Life Cycle Assessment (LCA) frameworks. Reducing cutting waste mitigates the environmental burden of steel production, which carries a high carbon footprint (0.8 $kgCO_2eq$ per kg in the Thai context). Incorporating these results into LCA models could provide a more comprehensive evaluation of construction system impacts and pave the way for developing Best Available Techniques (BAT) for low-carbon construction, as suggested by the European Commission [19]. Importantly, the concept of "Multiple Stock Length Optimization" validated in this study holds significant potential for application in other construction sectors, particularly in Hot Rolled Structural Steel projects for high-rise buildings and industrial plants. Major manufacturers in Thailand, such as Siam Yamato Steel, provide standard stock lengths of 6, 9, and 12 meters [20]. Prior research by Malai [21] demonstrated that optimizing structural steel cutting using a single stock length (6 m) could reduce waste by 6.11%. However, applying the findings of the current study—specifically the Combined Stock Lengths strategy—to utilize a mix of 6, 9, and 12-meter stocks would likely yield even superior material efficiency and cost savings for complex steel structures.

For future research, particularly in large-scale construction projects with high complexity and extensive cutting lists (Large-scale problems), the Integer Linear Programming (ILP) model may face computational time constraints. To address this, it is recommended to integrate Heuristic or Meta-heuristic approaches, such as Genetic Algorithms (GA), which have proven effective in optimizing 2D cutting stocks for furniture manufacturing as demonstrated in previous studies [22]. Additionally, adopting Artificial Intelligence (AI) and Machine Learning (ML) techniques to predict optimal cutting patterns could significantly enhance processing speed and flexibility for complex structural projects, paving the way for automated and intelligent construction management systems.

5. Conclusions

This research underscores the remarkable potential of applying Integer Linear Programming (ILP) in conjunction with the use of multiple standard rebar stock lengths (10 meters and 12 meters) to optimize cutting plans for wastewater treatment plant construction. Quantitative analyses confirm that combining both stock lengths significantly reduces waste and enhances material utilization rates compared to using a single stock length.

For DB12 rebar, the combined stock length approach achieved a material utilization rate of 96.86 %, with waste amounting to just 3.14 %. Similarly, DB16 rebar attained a utilization rate of 97.14 %, with waste reduced to 2.86 %. Most notably, for DB25 rebar, the combined approach yielded an exceptional utilization rate of 98.05 %, decreasing waste from 17.09% (using 12-meter stock) to a mere 1.95 %.The sensitivity analysis confirms that the ILP model remains robust under moderate increases in rebar demand.

This reduction in waste not only resulted in substantial material cost savings - up to 15.44 % for DB25 rebar compared to using 12 meter stock alone - but also led to a significant decrease in greenhouse gas emissions by 15.45 % for the same size. These findings highlight that systematic cutting planning, supported by appropriate tools and diverse stock length considerations, is a pivotal strategy for enhancing competitiveness, mitigating environmental impacts, and advancing sustainability in the construction industry. Integrating such approaches into practical workflows is an urgent necessity to promote intelligent resource use and support Thailand’s sustainable development goals.

Conflict of interest

The authors declared that this article has no conflict of interest.

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