Material Waste Analysis in Building Structural Works Using the Lean Construction Method

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ABSTRACT

The lean construction approach is a systematic framework offered to identify and minimize non-value-adding processes that cause material waste in construction projects, which contribute to inefficiencies, cost overruns, and decreased project performance. This study investigates the types and causes of material waste in the construction of a public infrastructure project by applying lean construction principles. Several challenges were observed during implementation, including frequent design modifications, specification changes, limited storage capacity, and various on-site technical issues. The research utilizes key project documents such as the S-curve, Bill of Quantities (BoQ), and As-Built Drawings to analyze material use and waste patterns. The methodological steps include identifying high-cost materials, conducting a Pareto analysis, calculating installed material volumes, performing waste level assessments, and evaluating waste-generating activities based on lean waste categories. The findings reveal that the most prominent types of waste were defect, overproduction, waiting, and inventory. Defects were primarily caused by changes in building specifications. Overproduction occurred due to insufficient optimization during planning. Waiting-related waste was a result of untimely ordering of materials, while inventory-related waste stemmed from inadequate material storage practices. The identification of high-cost materials and Pareto analysis revealed four types of materials with the highest potential for waste generation: 16 mm diameter reinforcing steel bars (D16), 8 mm diameter reinforcing steel bars (Ø8), Portland cement, and 13 mm diameter reinforcing steel bars (D13), and according to the waste level analysis, the highest waste level percentage is D13 Deformed Steel Bars with a waste volume of 1138,18 kg and a waste level of 4,035%. The study underscores the importance of proactive material management and lean-based planning to enhance project efficiency and sustainability.

Keywords: material waste, lean construction, construction efficiency, waste management

INTRODUCTION

The construction industry significantly contributes to global waste production, generating a substantial portion of the waste in landfills [1], [2]**.** Waste in construction can be defined as any activity that consume significant resources without generating added value [3]. More specifically, construction waste refers to materials resulting from construction activities that are no longer valuable or useful to the project owner [4]. These may include surplus materials, damaged components, or materials discarded due to errors or inefficiencies.

Among the most prevalent factors commonly contribute to the generation of construction waste are frequent design changes during implementation, lack of skilled labor, improper selection of construction methods, and inadequate project planning and control [5]. In practice, it is highly improbable for a construction project—especially one involving building construction—will produce no residual materials.

Therefore, to reduce environmental impact and economic losses, it is necessary to identify the root causes of excessive construction waste [6], [7], [8]. Relevant stakeholders can consider better waste management strategies that will benefit both the construction industry and the environment [9], [10]**.** By improving the quality of waste management, it is expected that environmental impacts and

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associated costs can be reduced, which represents one of the stages in the design process that involves the application of design principles, thereby encouraging a more sustainable approach to construction [11].

A range of inefficiencies among construction contractors in Indonesia are discovered, which include schedule delays, repair to finishing work, damage materials on site, waiting for equipment and tools due to delayed decisions [12]. Excessive design changes, low-skilled workers, poor decision-making, poor coordination among related parties, weak planning and control, delays in material delivery, and inappropriate work methods are some of the causes of inefficiency [13], [14]. Therefore, a comprehensive approach is needed, which includes improving communication among stakeholders, enhancing worker training, and implementing stricter waste management practices [9]. Construction waste itself can be classified into two categories based on its causes, namely indirect waste and direct waste. Direct waste consists of physical remnants of materials that are damaged or unused and cannot be repurposed during the construction process [15]. Indirect waste, by contrast, is less visible and refers to the monetary loss arising from excessive material use beyond what was initially estimated, even if such excess is not physically identifiable as discarded material on site [16].

Effective waste management is closely linked to broader goals, namely sustainability and cost efficiency in the construction industry, such as construction waste management aimed at reducing material consumption, promoting reuse, and maximizing recycling potential [17], [18].

One of the strategic approaches increasingly adopted to improve project performance is the lean construction approach as an effort to address existing issues. Lean construction emphasizes minimizing waste and maximizing value across all stages of the project. Although this approach requires considerable time and coordination during the planning and design phases, it can lead to improved efficiency and better cost control throughout the project [19], [20]. The application of lean construction principles can result in significant improvements in waste reduction and overall project efficiency, ultimately benefiting both the environment and the stakeholders in construction projects [21], [22]. In the end, the implementation of lean construction practices will foster a system of continuous improvement within projects.

This study focuses on material waste generated during the construction of the Social Rehabilitation Center Building in Medan, which began in 2022 to support recovery programs for individuals overcoming drug addiction. Several challenges encountered during the project's implementation included design changes, specification revisions, limited storage space, and various other technical constraints. These factors significantly contributed to increased material waste and inefficiencies in the project. This research was conducted to systematically identify the causes of waste in the project by adopting the lean construction framework.

RESEARCH METHODS

This research employs a qualitative approach grounded in the principles of lean construction to analyze material waste in construction projects. The qualitative method is selected for its strength in capturing a deep understanding of field conditions, allowing the researcher to explore context-specific problems through systematic reasoning and logical interpretation [23], [24]. This approach is highly suitable for construction environments, where on-site complexities often cannot be analyzed using standardized parametric methods [25]. The methodology is designed to be objective so that the formulation of solutions can be aligned with the realities of project execution on-site.

The study is carried out in three main stages. First, relevant variables contributing to material waste are identified. These variables are determined based on a literature review, expert consultation, and direct field observations. Each variable is then assigned a value using a qualitative weighting scale to determine its level of significance and impact on the occurrence of material waste. In the second stage, non-parametric statistical techniques are used to examine the relationships among variables. The final stage is carried out by considering lean construction principles, focusing on identifying strategies to minimize waste and enhance value on-site. Through a structured research process, this study is expected to address material waste in the construction sector.

Material Data Processing and Waste Analysis

Identification of High-Cost Materials with Waste Potential

The initial stage of this research focuses on identifying the types of construction materials that contribute significantly to the overall cost structure of the project. This step is critical in establishing a clear understanding of which materials are most frequently used and in which components or phases of the construction they are applied. Recognizing these dominant materials provides a foundation for further analysis, particularly in relation to potential material waste and opportunities for optimization.

To achieve this, data collection is conducted using a combination of sources. Key documents such as the Bill of Quantities (BoQ) are examined to extract detailed cost allocations and volume estimates for each material. Construction drawings are reviewed to determine the specific application of materials across structural and architectural elements. In addition, direct field observations are carried out to validate the accuracy of the documented data and to capture any discrepancies or variations that may occur during actual implementation. By triangulating these sources, the research ensures a comprehensive and contextually grounded identification of material usage patterns within the project.

Pareto Analysis

Pareto analysis is employed to determine dominant material types based on their cost contribution to the project. The analysis begins by calculating the weight of each construction task using the following formula:

$$\text{Task Weight (\%)} = \frac{\text{Task Value}}{\text{Total Project Cost}} \times 100\%$$

After calculating the weights, the tasks are sorted from highest to lowest and their cumulative weight is determined. Tasks with cumulative weights up to 80% are considered dominant and are used as the basis for selecting materials for waste level analysis. These dominant tasks serve as the basis for identifying key materials to be analyzed further in the waste level assessment. This method ensures that the study concentrates on the most financially significant materials, thereby maximizing the relevance and impact of the findings.

Waste Level Analysis

To quantify the extent of material inefficiency, the waste level is calculated to determine the amount of material wasted during the construction process. The calculation is conducted using the following formula:

$$\text{Waste Level (\%)} = \frac{\text{Amount of Waste Material}}{\text{Total Material Used}} \times 100\%$$

This analysis is essential for identifying which materials are most vulnerable to wastage, thereby guiding targeted interventions in material planning, procurement, and on-site handling. Understanding the specific materials with high waste levels can help project teams develop more effective strategies to reduce loss, enhance resource efficiency, and promote more sustainable construction practices in future projects.

Identification of Waste-Generating Processes Based on Lean Construction

The final stage of this research focuses on analyzing construction activities that have the potential to generate waste, using the *lean construction* framework as described in [26]. This framework, which refers to the seven classic categories of waste in the *lean* method, provides a more structured perspective for identifying and critically evaluating inefficiencies in construction processes. Each waste category represents *non-value-adding activities* that are commonly found in construction projects.

The types of waste examined include: defects, which refer to errors or the need for rework due to quality issues; overproduction, which occurs when construction outputs exceed actual demand; waiting, involving delays caused by uncoordinated workflows or material shortages; over-

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processing, referring to unnecessary or redundant steps that do not contribute to added value; motion, which captures inefficient physical movement by workers or equipment; transportation, involving the needless relocation of materials or tools; and inventory, characterized by excess material accumulation that may lead to deterioration, misplacement, or cost inefficiencies.

This research seeks to map patterns of waste—often overlooked in daily operations—into the categories described above. Based on these findings, recommendations grounded in lean principles are proposed with the aim of improving material efficiency, enhancing workflow reliability, and promoting sustainable construction practices.

RESULT AND DISCUSSION

This study aims to evaluate the types of construction materials with the highest potential for generating waste and to identify the key construction processes responsible for material inefficiencies using the lean construction approach. The data were sourced from the Bill of Quantity (BoQ) of the Rehabilitation Center Construction Project (Phase II) managed by the Department of Social Affairs, Medan City. The BoQ provides details on material volumes and unit prices.

Identification of High-Cost Materials with Waste Potential

The initial step in data processing involved identifying materials with the highest total cost. Materials categorized as trading consumables were ranked based on their total value, calculated by multiplying volume and unit price. Based on this identification, eight materials were listed in descending order of cost. The top four materials, D16 Deformed Steel Bars, Ø8 Plain Steel Bars, Portland Cement, and D13 Deformed Steel Bars, were identified as contributing more than 10% each to the project's total material cost.

Table 1. Identification of unit prices and quantities contained in the Bill of Quantity

No.	Material	Unit	Volume	Standard Activity Unit Price	Total Price
1	D16 Deformed Steel Bars	kg	75454,60	Rp. 23.812,-	Rp. 1.796.760.776,-
2	Ø8 Plain Steel Bars	kg	75875,37	Rp. 20.794,-	Rp. 1.577.731.578,-
3	Portland Cement	kg	506414,12	Rp. 1.900,-	Rp. 962.186.832,-
4	D13 Deformed Steel Bars	kg	28209,83	Rp. 23.812,-	Rp. 671.745.872,-
5	Crushe Stone 2-3	kg	1323537,96	Rp. 323,-	Rp. 427.759.416,-
6	Concrete Sand	kg	906564,93	Rp. 129,-	Rp. 116.558.348,-
7	Gravel (max 30 mm)	kg	28468,44	Rp. 323,-	Rp. 9.200.827,-
8	Sand Fill	kg	14,08	Rp. 209.070,-	Rp. 2.943.706,-

Pareto Analysis

Pareto analysis was implemented to determine dominant materials that significantly contribute to the overall cost. The weight of each material was calculated by comparing its total cost to the total material expenditure. The cumulative weight analysis revealed that the top four materials accounted for approximately 90% of the total project material costs. As a result, these materials were selected as the focus for further waste-related analysis.

Tabel 2. Pareto Analysis Calculation Results

No.	Material	Unit	Volume	Standard Activity Unit Price	Total Price	Weight Percentage	Cumulative Weight Percentage
1	D16 Deformed Steel Bars	kg	75454,60	Rp. 23.812,-	Rp. 1.796.760.776,-	32,29%	32,29%
2	Ø8 Plain Steel Bars	kg	75875,37	Rp. 20.794,-	Rp. 1.577.731.578,-	28,35%	60,54%

No.	Material	Unit	Volume	Standard Activity Unit Price	Total Price	Weight Percentage	Cumulative Weight Percentage
3	Portland Cement	kg	506414,12	Rp. 1.900,-	Rp. 962.186.832,-	17,29%	77,93%
4	D13 Deformed Steel Bars	kg	28209,83	Rp. 23.812,-	Rp. 671.745.872,-	12,07%	90,00%
5	Crushe Stone 2-3	kg	1323537,96	Rp. 323,-	Rp. 427.759.416,-	7,69%	97,69%
6	Concrete Sand	kg	906564,93	Rp. 129,-	Rp. 116.558.348,-	2,10%	99,78%
7	Gravel (max 30 mm)	kg	28468,44	Rp. 323,-	Rp. 9.200.827,-	0,17%	99,95%
8	Sand Fill	kg	14,08	Rp. 209.070,-	Rp. 2.943.706,-	0,05%	100%

Thorough management of the materials listed in Table 2 can serve as a waste reduction strategy by focusing on monitoring and optimizing the four main materials with the highest cost contributions, namely D16 Deformed Steel Bars (32.29%), Ø8 Plain Steel Bars (28.35%), Portland Cement (17.29%), and D13 Deformed Steel Bars (12.07%).

These four materials alone represent approximately 90% of the total material costs, as indicated by the steep rise in the cumulative percentage line. After this point, the remaining materials, Crushed Stone 2-3, Concrete Sand, Gravel (Max. 30 mm), and Sand Fill, have minimal cost contributions, with the cumulative curve beginning to flatten. Four out of eight materials that account for the majority of the cost impact illustrate the Pareto Principle (also known as the 80/20 rule), which underscores the importance of focusing on these dominant materials when formulating waste reduction strategies and improving material management efficiency. Effective monitoring and optimization of the top four materials could yield significant cost savings and contribute to more sustainable project execution [27], [28]. To further enhance material management, it is essential to implement targeted waste reduction strategies specifically focused on the identified high-cost materials, ensuring efficient resource allocation and minimizing overall project expenses [29]. Implementing inventory control techniques such as ABC and EOQ analysis can significantly enhance material management efficiency and reduce costs associated with construction waste [30].

Waste Level Analysis

Based in the volume calculations derived from the as-built drawings and data, the resulting waste level is as follows.

Table 3. Waste Level Analysis Results

No.	Material	Unit	Volume	Installed Volume	Waste Volume	Waste Level (%)
1	D16 Deformed Steel Bars	kg	75454,60	74829,40	625,20	0,829%
2	Ø8 Plain Steel Bars	kg	75875,37	75071,39	803,98	1,060%
3	Portland Cement	kg	506414,12	502446,83	3967,29	0,783%
4	D13 Deformed Steel Bars	kg	28209,83	27071,654	1138,18	4,035%

It can be seen in the table above that the material with the highest waste level percentage is D13 Deformed Steel Bars with a waste volume of 1138,18 kg and a waste level of 4,035%.

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Identification of Waste-Generating Processes through Lean Construction

The identification of waste-generating processes was performed using the seven categories of waste defined in lean construction principles: defect, overproduction, waiting, overprocessing, motion, transportation, and inventory.

1. Defect waste emerged due to specification and size changes resulting from contract addenda. These changes required rework or material adjustments, leading to significant material waste.
2. Overproduction was observed in steel bar installation work. This occurred due to poor material optimization, leading to production exceeding actual demand. Although not significantly impactful, this waste can be minimized by applying Just In Time (JIT) practices.
3. Waiting occurred due to delays in material deliveries to the construction site, which led to idle time and forced overtime, thus increasing project costs. The delays were attributed to poor coordination between contractors and suppliers, as well as logistical limitations.
4. Overprocessing in this project was minimal. Based on interviews with the site manager, there were few instances of unnecessary or non-value-adding work.
5. Motion waste was identified when workers performed unnecessary movements due to a lack of task knowledge or improper material placement. Unskilled workers hindered workflow efficiency, which was resolved by replacing them with more competent personnel.
6. Transportation issues were noted when materials and equipment were not located where needed. Scattered materials disrupted site logistics and increased the risk of damage. Reorganizing storage areas was recommended to improve material handling efficiency.
7. Inventory waste occurred due to improper storage conditions. Cement placed directly on floors and steel exposed to weather elements were found damaged. Storage areas lacked weather protection and security, and retrieval processes were inefficient. Proper inventory management systems are necessary to prevent material loss and degradation.

CONCLUSION

The results of the data analysis, supported by site observations, reveal that the predominant sources of material waste in the project align with four principal categories of lean construction waste: defect, overproduction, waiting, and inventory. These forms of waste manifest through various on-site inefficiencies, such as material damage due to rework, excess ordering beyond actual demand, idle time caused by uncoordinated scheduling, and the accumulation of unused or poorly stored materials. Furthermore, the Pareto analysis conducted in this study identified four primary materials that contributed most significantly to the total material waste: D16 steel bars, Ø8 steel bars, Portland cement, and D13 steel bars. And according to the waste level analysis, the highest waste level percentage is D13 Deformed Steel Bars with a waste volume of 1138,18 kg and a waste level of 4,035%. Notably, these materials with the highest cost components in the material budget highlight the direct financial impact of material waste when not properly controlled. Based on these findings, an integrated material management system from the planning stage to the execution of the project—consisting of effective monitoring, accurate forecasting, and better coordination between procurement, storage, and field operations is highly needed to minimize material waste, thereby contributing to increased efficiency, cost control, and sustainability in the implementation of construction projects.

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