

A LEAN-BASED APPROACH TO STREAMLINE PRODUCTION AND REDUCE WASTE IN PRECAST CONCRETE PANEL MANUFACTURING

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ABSTRACT: The demand for faster, more sustainable construction methods has driven innovation in off-site manufacturing, including innovation for the construction of precast concrete panels. These panels progress through a mass production-like process that ensures consistency and efficiency. Completed panels are then transported to construction sites for seamless assembly. This paper presents a case study conducted at a precast concrete panel manufacturing facility in Edmonton, Canada, where lean philosophy is applied to analyze and optimize the production process. Through direct observation, questionnaires, and root cause analysis, inefficiencies are identified, and alternative lean-based solutions are developed, such as design standardization and waste elimination. root cause analysis. These solutions include developing a standardized panel design based on the most used R-values identified from historical data, implementing waste elimination strategies, and creating new drafting templates for production. These templates address communication challenges between the engineering team and shop workers by eliminating redundancy, introducing colour coding according to used material, retaining relevant information only, and simplifying the written expression in the production drawings. Additionally, a Python-based tool is developed to optimize the rebar-cutting process, reduce material waste and associated costs. The study underscores the transformative effect of integrating lean methods and technology in off-site construction to enhance operational efficiency, productivity, and sustainability.

1. INTRODUCTION

The demand for efficient and sustainable construction methods has led to the widespread adoption of precast concrete panel manufacturing in the construction industry. Precast concrete offers numerous advantages, including faster production, improved quality control, and reduced material waste, making it an ideal solution for modern construction challenges. However, despite these benefits, inefficiencies in workflow, extended lead times, and material waste continue to hinder productivity in precast concrete facilities. One of the most effective strategies to streamline production and minimize waste is the application of lean construction principles (Alsakka et al., 2022a). Lean principles aim to eliminate waste (Muda), which includes non-value-adding activities such as waiting, rework, and excess inventory; reduce overburden (Muri); and minimize process variability (Mura). Non-value-adding activities are a specific type of Muda that do not directly benefit the customer.

In precast concrete manufacturing, these principles can enhance production flow, reduce lead times, and optimize resource utilization. This study presents a case study of a precast concrete panel manufacturing facility in Edmonton, Canada, where lean methodologies were implemented to analyze and improve production efficiency. The objective of this study is to identify production inefficiencies in a precast concrete manufacturing facility and apply lean methodologies to improve workflow, reduce material waste, and enhance project delivery time. Driven by the demand for scalable, sustainable construction methods in response to Canada's housing needs, the research uses direct observation, root cause analysis, and lean-based optimization to pinpoint inefficiencies and tackle them. It proposes practical solutions, such as design

standardization, shop drawing optimization and rebar-cutting optimization using a Python-based tool. Overall, the study highlights how lean principles can significantly improve the efficiency and productivity of off-site construction practices.

2. LITERATURE REVIEW

According to a September 2023 estimate by the Canada Mortgage and Housing Corporation (CMHC), Canada requires approximately 3.5 million more housing units by 2030 to restore affordability (CMHC, 2023). This goal implies that the current pace of housing construction must be tripped by 2023 (Bellemare, 2024). Therefore, the construction industry must adopt more efficient building practices. Precast concrete, with advantages such as durability, greater span-to-depth ratios, faster construction, and reduced waste, has emerged as a globally preferred solution for various structures, including bridges, parking garages, commercial buildings, and multi-family residential complexes (CPCI, 2017; Xiaosheng & Hamzeh, 2020). While developed countries leverage precast concrete for its economic, environmental, and social-friendly benefits, developing countries focus on its sustainability benefits to meet rapid urbanization demands (Li et al., 2014). Pursuing a prefabricated concrete construction approach suits Canada's extreme weather conditions because it provides a controlled environment for production. The construction industry is inherently complex and is often described as a 'wicked problem' due to issues such as poor communication and misunderstandings of stakeholders' values, needs, and perspectives. These issues contribute to wasted time, material, and project delays. Studies indicate that the construction process in precast concrete factories is not immune to inefficiencies such as waste and extended lead times (Xiaosheng & Hamzeh, 2020). Some of the most common challenges in the precast concrete industry in developing countries are long lead time, inefficient workflows, and embedded process waste. Hence, improving workflow and processes is crucial for enhancing productivity, quality, lead time, and team commitment within the construction industry (Ballard, 1999; Chen et al., 2003; Serpell et al., 1996).

From a lean construction perspective, the common types of waste in mass production, such as overproduction, waiting time, transportation inefficiency, excess inventory, processing, movement inefficiency, and rework, are also found in precast concrete manufacturing (Darwish et al., 2020). Rebar cutting is a significant source of waste in precast concrete companies. This waste often results from the large differences between required and standard rebar lengths. This problem is known as the one-dimensional cutting stock issue (Al-Zubaidy et al., 2016). Therefore, there is always a demand for improving production rates and reducing waste. Lean production was initially created within the Toyota Production System but has since been adopted by various industries due to its remarkable advantages that enhance production and minimize waste. One of the many industries that have adopted lean principles is the construction industry, specifically modular construction. Many case studies on precast concrete companies have demonstrated the significant effects of applying lean principles to enhance production rates, reduce lead times, ensure continuous flow, and minimize waste. For instance, a study conducted by (Alsakka et al., 2022b) highlighted the effects of the application of lean principles in construction manufacturing. They referenced two case studies. The first was a case study by (Moghadam & Al-Hussein, 2013) conducted at a modular construction facility, which found that minimizing waste could reduce the time needed to fabricate modules for a two-story building from 36 days to 30 days and improve the probability of timely project completion from 97% to 98.5%. The second case study was done by (El Sakka et al., 2016) at a precast factory, which suggested that implementing lean strategies, such as reducing batch and inventory sizes and applying the 5S program, could potentially cut production lead time by 50%.

Time is an essential metric in lean manufacturing, with various aspects such as wait time, processing time, cycle time, and customer demand or lead time benefitting from consideration. This case study focuses on a precast concrete company that has adopted numerous lean principles but still faces inefficiencies where lead time exceeds customer demand. This indicates that the Takt time (the production time considering customer demand) is either inefficient or suboptimal. This inefficiency results in wasted time and project delays. This paper aims to enhance the company's production efficiency and minimize waste through the application of various lean methods and principles. It begins by identifying customer needs, following the five fundamental principles of lean thinking (Identifying value, mapping the value stream, creating flow, establishing pull, and continuous improvement) to foster continuous improvement (kaizen). The objective is to define a value for both the management team and shop floor workers, utilizing the "5 Whys" method

to uncover the root cause of bottlenecks in the process. Subsequently, lean principles and methods are employed, including standardization, waste minimization, and the elimination of all kinds of Muda, Muri, and Mura, paving the way for further improvement in this case study. Despite the growing application of lean principles in precast concrete construction, several research gaps remain:

- 1- Lack of structured lean implementations specifically targeting drawing standardization and its direct impact on production in ribbed structure panel manufacturing.
- 2- Limited studies demonstrating the practical integration of custom digital tools (e.g., Python-based optimization) within lean frameworks.

3. COMPANY INTRODUCTION

The company featured in the case study provides a wide range of products, offering a unique ribbed structure that incorporates plywood, rebar, Styrofoam, wire mesh, and concrete to achieve the required thermal and structural strength. These panels are designed to provide practical application for both interior and exterior finishes. Figure 1 shows the different layers of the wall and floor panels produced by the company.

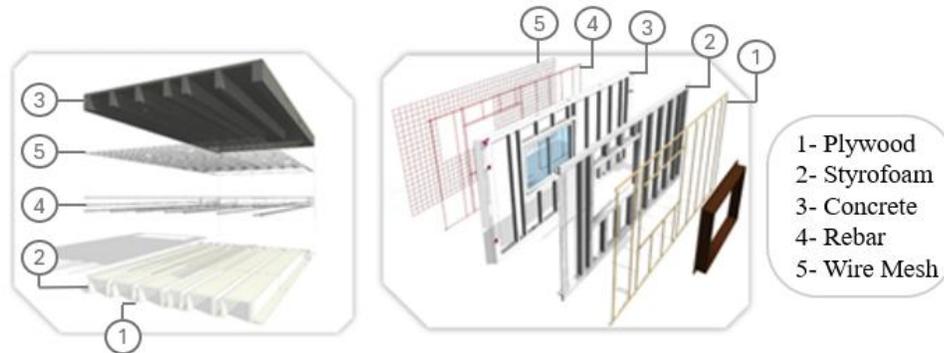


Figure 1: Product material breakdown

4. METHODOLOGY

The case study was initiated by a meeting with the company's owner to identify their values. It was revealed that end-users most strongly value on-time delivery and receiving the required quality of products. Meanwhile, the management team's values were on-time project delivery, production improvement, and minimal waste. This paper aims to identify current problems in the system via a questionnaire and conduct a thorough analysis of these responses to find solutions that will optimize the manufacturing process while minimizing various forms of waste. To this end, the authors visited the factory, observed the production process, and held meetings with the engineering team and shop workers to gather information regarding the production process. Initially, the desired data focused on information about bottlenecks and waste resources. However, as the process progressed, information regarding the cause of delays and idle time of engineers and shop workers became more valuable. For instance, nearly all workers expressed having difficulties understanding specific details in shop drawings, leading to production delays. This was because instructions were written in English, making them challenging to understand due to the workers' limited proficiency in English.

Other information, such as idle time among workers while others were overburdened, led to identifying the bottleneck in the system. Therefore, the "5 Whys" lean technique, which involves asking "Why?" five times to find the root cause of the problem, was employed. This would prevent the bottleneck from occurring in the future while also proposing solutions for each "why?" that caused the main problem. So, the "5 Whys" method was used to trace key issues-such as delays in Styrofoam cutting and rework from unclear drawings-back to root causes. Identified inefficiencies were prioritized based on their frequency, impact on production, and ease of resolution using lean tools. Moreover, significant time and cost inefficiencies were discovered due to non-standardized product design. This resulted in numerous meetings with customers to tailor panels to their specific thermal resistance (R-value) requirements. While this customization seemed beneficial to customers, it caused additional challenges for the company due to requirements for additional

engineering hours to create a unique design and Revit families. Furthermore, it required explaining the design to fellow engineers and workers involved in the project, increasing the workload without extra compensation for those hours. In addition, another task involved 1D optimization of rebar bars. Rebar is an essential component in construction, thereby often causing significant material waste in the cutting process. To tackle this issue, a Python code was developed to optimize the cutting list, aiming to minimize waste and optimize resource utilization.

This paper explores different issues across multiple phases of the manufacturing process. It also details the utilization of various lean principles to overcome the current obstacles in the system. This was achieved by utilizing the A3 lean process as follows: Firstly, a comprehensive analysis of the problems was conducted. Secondly, different scenarios were evaluated. Lastly, reasonable countermeasures were discussed. To successfully implement these solutions, the authors engaged in extensive conversations with workers in the precast plant. Then, the authors conducted a feasibility study to determine their suggestions. Finally, the authors worked closely with the engineering team to study the applicability of reasonable suggestions, exploring the team’s ability to implement these changes in their system and developing alternative approaches in case of rejection. Subsequently, the efficiency gains and the stakeholders' satisfaction will be addressed following the implementation of the solutions.

5. BOTTLENECK

While observing the process, delays and idle time among workers in the material preparation phase became apparent. When asking for clarification about current tasks to understand the reason behind the idle time, the “5 Whys” method was used to uncover the root cause of the system’s bottleneck. Table 1 provides a comprehensive summary of the process bottleneck that comes from the Styrofoam cutting station, leading to delays and idle time among workers. This bottleneck is caused by delays from the engineering team when producing the shop drawings due to a lack of a standard design. This created more obstacles, causing the engineering team to produce shop drawings and cutting lists for every panel instead of a consolidated list for the whole project.

Table 1: “5 Whys” method

WHY:	Material preparation is not done on time
WHY:	Styrofoam cutting phase is consistently delayed (Styrofoam cutting in particular)
WHY:	Shop drawings are produced per panel (NO consolidated list)
WHY:	The engineering team is behind schedule
WHY:	No standard design (variation in Styrofoam shapes)

6. DESIGN STANDARDIZATION

In precast construction, standardization of the design is an important lean concept that plays a pivotal role in enhancing the efficiency and quality of the manufacturing process. The current practice in the precast company consists of lengthy meetings between the management team, the client, and a representative of the engineering team to find a tailored design that fits the needs of each client. This process includes considering the energy aspect of the design and accomplishing the effective R-value desired by the client through either batt insulation or through the thickness and type of the Styrofoam itself. To solve this issue and deal with the fifth “Why?”, the authors conducted meetings with the company’s energy engineer, where a standard design was developed for clients to pick from.

The design was developed based on the most common R-values for previous projects. Table 2 and Table 3 demonstrate the dimensions of the new Styrofoam flat and U-shapes with the corresponding R-values and insulation type based on whether it’s below-grade (basement) or above-grade.

Table 2: Dimensions of the new flat shapes

Location	Effective R	Precast Eff. R	Batt	U Type	Flat Dimensions
Below-grade	20	6	Batt 18	EPS Type1	1" x 19.5"
Below-grade	14	14	NA	EPS Type1	3.25" x 19.5"
Below-grade	24	24	NA	EPS Type1	8" x 18.5"
Above-grade	18	6.5	Batt 18	EPS Type1	1" x 20.5"
Above-grade	18	18	NA	EPS Type1	6" x 19.5"
Above-grade	22	22	NA	EPS Type3	6" x 19.5"

Table 3: Dimensions of the new U-shapes

Location	Effective R	Precast Eff. R	Batt	U Type	U Dimensions
Below-grade	20	6	Batt 18	EPS Type1	1" x 2.25" x 8"
Below-grade	14	14	NA	EPS Type1	1" x 2.25" x 8"
Below-grade	24	24	NA	EPS Type1	1" x 2.25" x 8"
Above-grade	18	6.5	Batt 18	EPS Type1	1" x 1.25" x 6"
Above-grade	18	18	NA	EPS Type1	1" x 1.25" x 6"
Above-grade	22	22	NA	EPS Type3	1" x 1.25" x 6"

7. SHOP DRAWINGS OPTIMIZATION

While completing surveys, workers expressed their frustration regarding the shop drawings. Their primary issue was that the drawings were intimidating due to the excessive details and were hard to follow. In response to this issue, the drawings were analyzed and improved versions were provided that prioritized the satisfaction of both the engineers and workers. The current drawings consist of four different drawings for each panel. The contents of the drawings prior to adjustment are described in further detail below.

The Styrofoam view drawings contain:

- Project, client, and drawing information
- The panel in Styrofoam view and all Styrofoam shapes are properly labelled (Styrofoam view highlights the Styrofoam shapes and diminishes other elements).
- Diagonal, horizontal, and vertical dimensions.
- Horizontal and vertical sections in Styrofoam view wherever the panel changes shape.
- Detailed dimensions for all the details in the sections.
- A table containing the panel's information: mark, area, volume, and weight in tons.
- A callout to clarify the labels and dimensions.
- Excessive notes and unnecessary details, such as "lifting anchors need to be checked".
- Green cumulative dimensions for the lifting anchors from left to right.
- Red dimensions for the openings.
- Checklist to keep track of what has been done during production.

It is easily observed that this list contains repetition, unnecessary details, and notes that do not concern the workers. The excessive number of detailed dimensions led to confusion among the workers, resulting in frequent interruptions by the engineers to clarify basic information, such as the association of dimensions

and clarifications of close measurements. Consequently, engineers who have already invested 3 hours and 55 minutes in this drawing must spend more time on it, causing overburden (Muri) on their part.

The plywood drawings contain:

- Project, client, and drawing information
- The panel is in plywood view, and all plywood pieces are labelled (plywood view highlights the plywood pieces and diminishes other elements).
- Three different tables of horizontal and vertical plywood used in the panel, and information including labels, type, length, count, and comments.
- A table containing the panel's information: mark, area, volume, and weight in tons.
- A legend of "corner plywood detail" in the right corner (not relevant to most projects).
- A detailed view of the top plate.
- Diagonal, horizontal, and vertical dimensions.
- Red dimensions for the openings.
- 3D view of the opening bucks.
- Same notes from the Styrofoam view.

This drawing takes approximately 1 hour and 55 minutes to produce. Evidently, some of the same issues from the Styrofoam drawing appear in the plywood drawing, such as repetition. The value of this drawing is limited, as the nailers are pre-nailed to the Styrofoam pieces prior to the assembly of the panel. Hence, there's no real value in the schedules and labels of plywood. Also, the legend in the right corner is part of the plywood template, and it's not relevant to most projects. The only valuable information from this drawing lies in the dimensions of the top plate. This information is important to workers as it guides them in cutting the pressure-treated lumber for the placement of the lifting anchors.

The Rebar drawings contain:

- Project, client, and drawing information.
- The panel in Rebar view with appropriate labelling.
- A table that contains Rebar bars' information.
- A table that contains the panel's information: mark, area, volume, and weight in Ton.
- Details of dimensions for curved Rebar bars.
- Diagonal, horizontal, and vertical dimensions.
- Same default note in all Rebar drawings.

This drawing takes 2 hours and 15 minutes to complete in the engineering station. It is also observed that repetition, unnecessary details, and notes without value appear. For this drawing, the Rebar bars beside the openings do not reflect the way they are implemented in real life. Also, a shared drawback between the previous drawings is over-processing. This makes the engineering phase contain all different types of what's known as waste in lean thinking: Muda, Muri, and Mura, which means waste, overburden, and unevenness.

The material takeoff drawings contain:

- Project, client, and drawing information.
- A table that contains the panel's information: mark, area, volume, and weight in tons.
- A table that contains detailed dimensions of the Styrofoam pieces.
- A legend that explains the labelling criteria.
- Legends that explain details of different Styrofoam pieces.

The engineering team created this drawing because of the company's push system, which results from market demands and process delays. After a thorough analysis of the current drawings and considering

the recommendations and opinions of both engineers and workers and to deal with the third and fourth "Why?", the number of drawings was reduced from four to two per panel, as well as a consolidated cutting list for the whole project. The following is a description of the improved drawings. The Styrofoam drawing contains the panel in Styrofoam view and the horizontal and vertical sections. Moreover, all kinds of waste and repetition were eliminated, and only the dimensions needed by workers were kept. The standard spacing for voids in the design is 2 feet center-to-center. To streamline the process, the dimensions for standard voids were removed, and we ensured that workers understand that if no specific dimensions are provided, the default dimension is the standard 2 feet. This approach highlights unique dimensions, making them more noticeable and reducing the likelihood of rework. Additionally, a colour-coding system was implemented to associate each dimension with its corresponding part clearly. This drawing now takes 3 hours and 5 minutes to produce, down from the original time of 3 hours and 55 minutes.

To improve the value of the Rebar and Plywood drawings, the two drawings were combined to create one drawing with only the valuable information. Combining the two drawings also decreased engineering time, going from 4 hours and 10 minutes for both to 2 hours and 30 minutes for the combined drawing. This optimization of shop drawings resulted in the engineering team being up to date with the schedule, with no delays on their part. Furthermore, they can produce a consolidated cutting list for the whole project. Figure 2 shows a sample of the consolidated cutting list. Moreover, obtaining the final count of all the Styrofoam pieces maximized the number of Styrofoam pieces produced from a 3-by-4-by-8 Styrofoam block by nesting the different shapes and pieces within each other. Figure 3 showcases a 2D cutting pattern of a Styrofoam block, which minimized waste and resulted in 48 U-shapes, 6 L-shapes, and 45 flat shapes. As a result of these changes, the cutting pattern in the CNC machine was optimized, leading to reduced material waste, increased efficiency, and a faster material preparation phase, ultimately addressing the final two "Whys".

Consolidated cutting list - By-Shape								
Family and Type	Label	Count	S Length	S Width	S Depth	S - Face Thickness	S - Side Thickness	Comment
SPC - Styrofoam - Flat, Shape: 19 1/2" Wide	PS1	58	86 1/2"	19 1/2"			1"	
PS1.24		58						
SPC - Styrofoam - Flat, Shape: 19 1/2" Wide	PS2	12	72 1/2"	19 1/2"			1"	
LR1: 8								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 7" x 8" 2	LR2	3	47"	7"	7 1/2"	1.34"	1"	
LR2.3								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 7" x 8" 3	LR3	2	55 3/4"	7"	7 1/2"	1.34"	1"	
LR3.5								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 7" x 8" 3	LR4	2	58 1/4"	7"	7 1/2"	1.34"	1"	
LR4.2								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR5	1	5"	5 1/2"	7 1/2"	1.34"	1"	
LR5.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR6	1	4 1/4"	5 1/2"	7 1/2"	1.34"	1"	
LR6.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR7	1	7"	5 1/2"	7 1/2"	1.34"	1"	
LR7.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR8	2	13 1/2"	5 1/2"	7 1/2"	1.34"	1"	
LR8.2								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR9	1	17 1/2"	5 1/2"	7 1/2"	1.34"	1"	
LR9.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR10	1	45 3/4"	5 1/2"	7 1/2"	1.34"	1"	
LR10.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR11	1	64 1/2"	5 1/2"	7 1/2"	1.34"	1"	
LR11.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR12	1	76"	5 1/2"	7 1/2"	1.34"	1"	
LR12.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR13	1	90 1/4"	5 1/2"	7 1/2"	1.34"	1"	
LR13.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR14	1	92"	5 1/2"	7 1/2"	1.34"	1"	
LR14.1								
SPC - Styrofoam - L-Shape, w/ Studer, w/ lip: 5 1/2" x 8" 2	LR15	3	196"	5 1/2"	7 1/2"	1.34"	1"	
LR15.1								

Figure 2: Consolidated cutting list

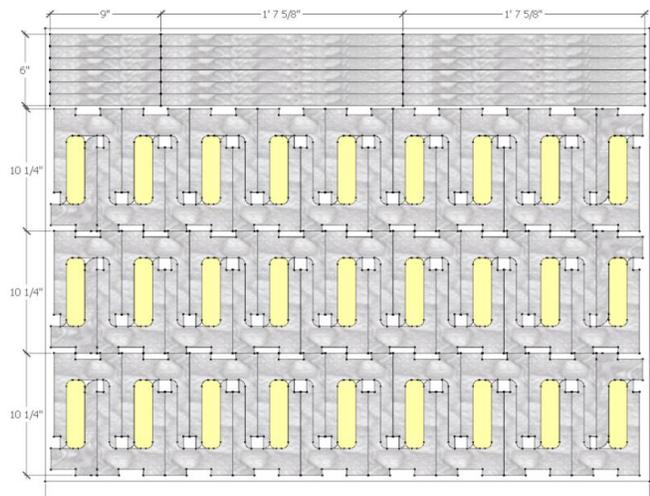


Figure 3: Optimized cutting pattern

8. ONE-DIMENSION OPTIMIZATION

During the survey, workers indicated significant rebar waste due to suboptimal cutting strategies and the absence of a project schedule. To address this, design standardization was implemented, reducing variability and accelerating the engineering phase. This improvement allowed for the development of complete and consistent shop drawings for the entire project, which, in turn, enabled the creation of a comprehensive rebar schedule. This schedule, exported from Revit as CSV files, was used as input for a Python-based optimization tool designed to reduce material waste and cost. Optimizing rebar cutting remains a persistent challenge in the construction industry. Our literature review indicates that while various studies have attempted to reduce waste, no solution has fully eliminated inefficiencies. The problem is categorized as a one-dimensional cutting stock problem, which is well-suited for linear programming (LP).

Given the large number of cutting combinations and variables involved, column generation was adopted as an effective method to dynamically produce feasible cutting patterns within the LP framework (Al-Zubaidy et al., 2016; Leite, n.d.).

In our developed tool, the decision variables represent the number of times a particular cutting pattern is used. The constraints ensure that all required rebar segment lengths are satisfied without exceeding the standard 20-foot bar length. The model's objective function minimizes total trim loss. Structurally, the optimized cutting instructions help reduce the need for splicing on-site, improve installation precision, and reduce delays, contributing to better construction flow. The Python code reads the full rebar schedule, evaluates available cutting patterns, and generates an optimized set of cutting instructions. Additionally, the tool is designed to reuse leftover pieces in subsequent cutting operations when their remaining lengths exceed the next required segment—thus further minimizing waste (Figure 4). This integration of LP with column generation not only improves material efficiency but also exemplifies how digital tools can support lean principles in construction manufacturing.

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Windows PowerShell
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Try the new cross-platform PowerShell https://aka.ms/powershell

PS G:\CIVE709 LEAN\project\code> python .\rebar_cutter.py .\rebar.csv -t csv
Optimizing a Chunk
Using wastes from previous chunk
Saved 0 inches of waste
Using wastes from 1 to 55
Saved 1109.84375 inches of waste
Using wastes from 56 to 69
Saved 352.28125 inches of waste
Finished optimizing a Chunk
Optimizing a Chunk
Using wastes from previous chunk
Saved 0.0 inches of waste
Using wastes from 70 to 72
Saved 0.0 inches of waste
Finished optimizing a Chunk

Rebar 1 to 1: | waste: 2.375 inches
Cut 1 pieces of 89.5 inches for RB8
Cut 1 pieces of 25.0 inches for RT6
Cut 1 pieces of 34.53125 inches for RW3
Cut 1 pieces of 91.59375 inches for RW4

Rebar 2 to 2: | waste: 0.46875 inches
Cut 1 pieces of 30.53125 inches for RD2
Cut 2 pieces of 104.5 inches for RR1

Rebar 3 to 4: | waste: 0.8125 inches
Cut 1 pieces of 30.59375 inches for RP10
Cut 2 pieces of 104.5 inches for RR1

Rebar 5 to 5: | waste: 2.0 inches
Cut 2 pieces of 83.0 inches for RR2
Cut 1 pieces of 72.0 inches for RR3

Rebar 6 to 6: | waste: 0.0 inches
Cut 1 pieces of 55.0 inches for RB9
Cut 1 pieces of 104.5 inches for RR1
Cut 1 pieces of 80.5 inches for RR4

Rebar 7 to 7: | waste: 0.0 inches
Cut 1 pieces of 55.0 inches for RB1
Cut 1 pieces of 104.5 inches for RR1
Cut 1 pieces of 80.5 inches for RR4

Rebar 8 to 9: | waste: 9.0 inches
RT8: Required 1.0, Produced 1.0, Met
RT17: Required 2.0, Produced 2.0, Met
RT9: Required 1.0, Produced 1.0, Met
RT10: Required 2.0, Produced 2.0, Met
RT11: Required 2.0, Produced 2.0, Met
RT12: Required 2.0, Produced 2.0, Met
RT13: Required 2.0, Produced 2.0, Met
RT14: Required 2.0, Produced 2.0, Met
RT15: Required 1.0, Produced 1.0, Met
RT16: Required 1.0, Produced 1.0, Met
RW1: Required 8.0, Produced 9.0, Met
RW2: Required 6.0, Produced 6.0, Met
RW3: Required 16.0, Produced 17.0, Met
RW4: Required 2.0, Produced 2.0, Met
RW5: Required 6.0, Produced 7.0, Met
RW6: Required 2.0, Produced 2.0, Met
RW7: Required 2.0, Produced 2.0, Met
RW8: Required 2.0, Produced 2.0, Met

Overall Total waste: 814.0625 inches
Total Standard Rebars Needed: 76.0
PS G:\CIVE709 LEAN\project\code>

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Figure 4: Rebar Cutting Instruction Sample

9. RESULTS AND DISCUSSION

9.1 VALUE ANALYSIS

Initially, this paper focused on identifying the key stakeholders, primarily the end-users of the product and the management team, and then analyzed each one's respective values. For the end-user, the critical values were timely project delivery and the fulfillment of the requested requirements. These values are essential, as they have a direct impact on the users' satisfaction and the company's reputation. The management team's values centered around optimizing operational efficiency, which included minimizing different types of waste, maximizing profit, enhancing productivity, and ensuring timely project delivery. The alignment of these values provided the foundation for a holistic approach that effectively addressed both end-user satisfaction and operational efficiency.

9.2 ROOT CAUSE ANALYSIS AND DESIGN STANDARDISATION

After the initial phase of the study, a comprehensive root cause analysis was conducted to identify the underlying causes that would lead to project delivery delays. The A3 problem-solving process was employed, and the "5 Why" technique was also used. Data was gathered through conducting surveys and holding meetings, all of which revealed that the lack of standardized designs was the root cause of the delays, causing a cascading effect. Engineers were constantly behind schedule due to the design process duration. This waste of time is classified as Muda in lean construction theory, and had a significant

contribution to project delay. To overcome this problem, designs were standardized, which had multiple benefits including reducing design process duration, as engineers would rely on predesigned templates. This also minimized muri (overburden) on engineers and workers, allowing for smoother transitions between project phases and enhancing the overall lead time. In addition, it laid the groundwork for further process improvements.

9.3 OVERPRODUCTION IN SHOP DRAWINGS

The other critical bottleneck was the overproduction of excessively detailed shop drawings. Its root cause was the lack of effective communication between the workers and the engineers. The unnecessary complex and detailed shop drawings caused confusion among workers, resulting in frequent inquiries, wasted time and materials, and a need for rework. These issues disrupted the workflow and created muda, as well as situations where workers were left waiting on the necessary drawings to proceed with their tasks. To address this bottleneck, workers were surveyed. It was discovered that they preferred simpler drawings with only the essential dimensions highlighted. This feedback led to the implementation of Poka-yoke (mistake-proofing) and Just-in-Time (JIT) principles, ensuring that only necessary details were provided when needed, reducing the number of shop drawings, eliminating overproduction and confusion, and significantly reducing material waste and rework. Additionally, Kaizen (continuous improvement) was adopted, introducing a consolidated Styrofoam cutting list to reduce interruptions. This was made possible by earlier design standardization. These interventions shifted the project from a push to a pull system, minimizing waste, improving takt time (the rate at which products need to be completed to meet customer demand), and enhancing lead time, resulting in a more efficient workflow.

9.4 ONE-D OPTIMIZATION: REBAR WASTE OPTIMIZATION

Following the kaizen culture and the recent trend of using AI to improve material efficiency (Shahrokhishahraki et al., 2024), a Python-based optimization tool was developed to address the significant waste in rebar utilization. The tool was designed to optimize the number of used rebars and generate precise cutting instructions, significantly reducing material waste and contributing to cost savings while minimizing environmental impact. Developing the Python tool highlighted the value of integrating technology into traditional construction, achieving precision and efficiency that would have been challenging to achieve with manual methods alone.

9.5 CONTRIBUTION TO ACADEMIA AND INDUSTRY: ADVANCED OFF-SITE CONSTRUCTION EFFICIENCY

This study presents a practical framework to enhance off-site construction workflows by applying lean principles—such as the “5 Whys” technique—to address key inefficiencies. In the case study, the absence of standardized designs and a unified cutting list created extra work, inconsistent material use, and delays, largely due to the manual and repetitive preparation of shop drawings and cutting instructions. To overcome these challenges, the team introduced standardized design templates and a consolidated list, enabling engineers to plan more effectively, reduce redundant tasks, and optimize material usage. These changes streamlined operations, minimized waste, and made the entire production process smoother, more predictable, and cost-efficient. Traditional lean tools like Kanban rely on manual processes, but this approach takes it further. By incorporating automation with data-driven optimization, it improves scalability and reduce material waste. It also goes beyond generic digital solutions by tailoring tools such as a Python-based rebar optimizer and simplified, multilingual shop drawings, specifically for precast construction, making the system both replicable and accessible across similar off-site manufacturing environments.

10. CONCLUSION

Applying lean principles enhanced operational efficiency and stakeholder satisfaction, starting with standardizing designs, which enabled consolidated Styrofoam lists and an optimized rebar-cutting schedule. This change also eliminated overproduction in shop drawings while reducing their complexity and number, minimizing confusion, rework, and material waste. The Python-based rebar optimization tool further exemplified the kaizen culture by reducing material waste and demonstrating technology's role in improving construction practices. Overall, standardization, Poka-yoke, JIT, and kaizen significantly improved productivity, efficiency, and cost savings while increasing stakeholder satisfaction, setting a benchmark for lean construction. One limitation of this paper is that it is based on a single case within a specific context, which means the results may not fully address the challenges in other facilities. Future work could focus on applying these strategies in different settings, exploring how digital tools such as BIM could support lean implementation, and evaluating the long-term impacts of these changes on efficiency and sustainability.

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