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A Lean-Based Approach to Streamline Production and Reduce Waste in Precast Concrete Panel Manufacturing

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Abstract

Question: How can lean principles, including design standardization, waste elimination, and process optimization improve production efficiency and reduce material waste in precast concrete panel manufacturing?

Purpose: To analyze inefficiencies within a precast concrete panel facility and demonstrate how lean methods can streamline workflow, reduce waste, and enhance production reliability through design standardization, drawing optimization, and rebar-cutting optimization.

Research Method: A case study using direct observation, worker surveys, engineering team interviews, and root-cause analysis (5 Whys), followed by development and testing of lean-based countermeasures including standardized designs, simplified shop drawings, consolidated cutting lists, and a Python-based cutting-stock optimization tool.

Findings: Suggested Lean improvements reduced engineering time for shop drawings, minimized rework, eliminated multiple forms of Muda/Muri/Mura, improved communication on the shop floor, and significantly decreased Styrofoam and rebar

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waste through standardized designs and optimized cutting patterns. The combined rebar–plywood drawing lowered engineering effort by 40%, and consolidated material schedules improved production flow and removed bottlenecks in material preparation.

Limitations: Performance improvements were not measured on the long-term cycles.

Implications: Lean tools, particularly waste elimination and material cutting optimization, can meaningfully enhance off-site construction by improving workflow reliability, reducing design variability, and strengthening collaboration between engineering and production teams.

Value for practitioners: This study provides a practical lean framework that other precast or modular manufacturers can replicate to reduce design effort, improve clarity of shop drawings, eliminate waste, and increase production efficiency using both lean thinking and simple digital tools.

Keywords: Lean thinking, precast concrete, prefabricated panels, standardized design, production improvement, optimizing the process

Paper type: Case study

Introduction

Modular and precast construction have increasingly been adopted as effective construction methods to address industry demands for faster project delivery, improved reliability, and enhanced production efficiency through factory-based manufacturing processes (Innella et al., 2019). Off-site systems allow work to be done in a controlled environment, enabling improved quality, reduced waste, and shorter construction schedules compared to traditional on-site processes (CPCI, 2017; Xiaosheng & Hamzeh, 2020). Despite the advantages of off-site manufacturing, studies of construction manufacturing facilities reveal persistent issues such as production delays, long lead times, poor information flow, and workflow variability that undermine production efficiency (Alsakka et al., 2022). Studies focusing on housing projects indicate that delays are primarily driven by deficiencies in site management, ineffective communication, and poor coordination among project stakeholders (Primayuda et al., 2019). Furthermore, construction projects are inherently complex due to fragmented processes, diverse stakeholders, and high uncertainty; therefore, lean construction has been identified as a viable approach to managing this complexity and improving project delivery outcomes (Ruan et al., 2016).

Building on the foundations of the Toyota Production System, lean thinking aims to eliminate non-value-adding activities (Muda), reduce overburden (Muri), and minimize variability (Mura) to create reliable and continuous production flow (Ballard, 1999; Koskela & Howell, 2002; Liker, 2004). Numerous studies have shown that applying lean principles in off-site and modular construction can reduce lead times, improve workflow reliability, and increase productivity, particularly by stabilizing production flow and reducing variability within construction manufacturing environments (Alsakka et al., 2022; Hamzeh et al., 2012; Moghadam, 2014). Although lean construction has demonstrated significant potential to improve project performance, the construction industry has not yet achieved consistent and mature implementation of lean principles across projects (Ead et al., 2024).

Furthermore, research has also identified persistent challenges in precast manufacturing, including rework, lack of standard designs, complex information flows, and

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material waste, particularly in reinforcement cutting (Al-Zubaidy et al., 2016; Darwish et al., 2020). These challenges often stem from variability in product design, excessive detail in shop drawings, and inefficient coordination between engineering and production teams.

This study investigates these issues within a precast concrete panel facility in Edmonton, Canada. Through direct observation, surveys, and root-cause analysis, the research identifies the sources of waste and bottlenecks in the production process. It then applies lean methodologies such as design standardization, drawing simplification, and one-dimensional optimization to enhance workflow, improve efficiency, reduce waste, and improve communication between engineering and production staff.

By integrating lean principles with practical digital tools, this study contributes to the growing body of research on improving workflow reliability and material efficiency in off-site construction. It provides a structured approach for addressing design variation, over-processing in information production, and waste in material preparation, offering insights that can support both industry practitioners and researchers.

Literature Review

Growing housing demand and the need for sustainable building solutions have increased the use of precast concrete systems in Canada, driving interest in faster, more efficient, and more industrialized construction methods (CMHC, 2023), such as precast concrete systems that offer better quality control, enhanced durability, reduced onsite labour requirements, and decreased material waste when compared to conventional construction approaches (CPCI, 2017). These characteristics have positioned precast concrete as a preferred construction method for residential, commercial, and infrastructure projects seeking higher productivity and sustainability performance (Li et al., 2014).

In construction projects, studies indicate that delays are primarily driven by deficiencies in site management, ineffective communication, and poor coordination among project stakeholders (Primayuda et al., 2019), which are often linked to non-value-adding activities that negatively affect time, cost, and quality, these elements align with the seven wastes originally defined in the Toyota Production System (Liker, 2004) and later adapted for construction contexts (Ily, n.d.). Therefore, lean construction has increasingly been recognized not only as a productivity-driven philosophy, but also as a strategic approach that contributes to environmental, economic, and social sustainability objectives in the construction industry (Hasan et al., 2024). Moreover, lean principles help reduce project complexity by creating more predictable workflows, improving coordination, and reducing uncertainty across project phases (Ruan et al., 2016).

A wide range of lean construction tools has been identified to support application, including standardization, waste elimination and the Five Whys root cause analysis (Muhammad et al., 2013). Through standardization, process variability can be reduced, which stabilizes the production cycle and enables systematic performance measurement and continuous improvement (Alsakka et al., 2022). These lean-driven improvements have been shown to strongly support sustainability outcomes by reducing non-value-adding activities, improving process efficiency, and minimizing material and energy waste (Hasan et al., 2024). In addition, mapping construction process flows has been proposed as an effective approach for identifying waste and achieving time reduction during the construction phase (Yahya & Mohamad, n.d.).

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Although standardization is fairly well known as a lean technique, it is not consistently applied across construction processes (Ikuabe et al., 2024). This limitation is increased by broader barriers to lean adoption, including insufficient lean awareness, limited training, a predominantly unskilled or semi-skilled workforce, fragmented industry structures, inconsistent workflows, and cultural resistance to change rooted in traditional practices (Pipaliya, n.d.). However, despite growing research interest, studies examining fully integrated lean implementation across all modular production stages remain limited, highlighting a critical gap in existing literature (Innella et al., 2019).

One persistent challenge in precast manufacturing is rebar waste, which arises because standard bar lengths rarely match required cut lengths, leading to inherent inefficiencies commonly referred to as the one-dimensional cutting stock problem (Al-Zubaidy et al., 2016). Traditional manual cutting often leads to excess scrap and inconsistent cutting patterns, whereas lean principles emphasize reducing material variability and improving resource utilization, making optimization-based cutting strategies particularly relevant (Leite, n.d.). Another critical challenge involves information flow, as complex or overly detailed shop drawings can confuse workers, leading to delays, errors, frequent clarification requests, and increased workflow variability and rework, thereby highlighting the need for improved communication in construction environments (Chen et al., 2003; Serpell et al., 1996).

While lean principles have been applied in many precast and modular construction contexts, important gaps remain in their practical integration. In particular, limited attention has been given to drawing optimization as a means of reducing waste in ribbed precast panel systems, and few studies integrate digital optimization tools, such as digital rebar-cutting optimization, within lean frameworks. This study builds on these gaps by examining how design standardization, simplified shop drawings, and digital rebar-cutting optimization can jointly improve workflow, reduce waste, and support continuous improvement in precast concrete production.

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.

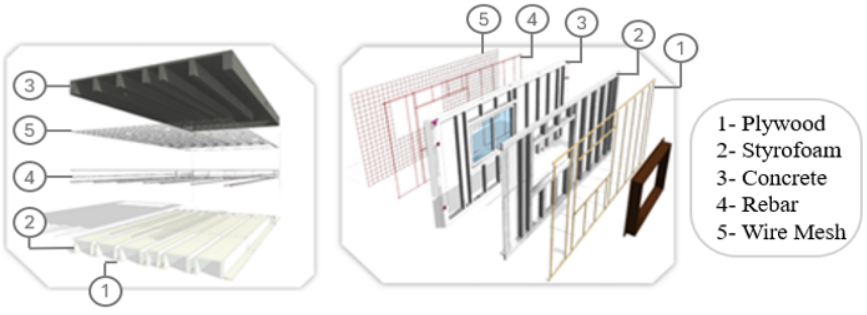


Figure 1. Material Breakdown

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Methodology

The case study began with a meeting with the company's owner to clarify the organization's core values. It was found that end-users prioritized on-time delivery and receiving products that meet the required quality, while the management team emphasized timely project completion, continuous production improvement, and reducing waste. Building on this understanding, the paper seeks to identify existing issues in the system through a structured questionnaire and to analyze the findings in order to recommend solutions that enhance production efficiency and minimize various forms of waste.

To support this investigation, the authors visited the factory, observed production activities, and met with both the engineering team and shop workers to collect detailed information about current practices. The initial focus was on identifying bottlenecks and sources of waste. However, as data collection progressed, challenges related to delays and idle time among both engineers and shop workers emerged as particularly significant. For example, nearly all workers reported difficulties interpreting certain details in the shop drawings, which contributed to production delays. These challenges stemmed largely from the drawings and instructions being written in English, a language many workers were not fully proficient in.

Additional observations included periods of worker idleness while other staff members were overburdened, which helped pinpoint the system's primary bottleneck. To better understand the root causes, the team applied the "5 Whys" lean technique, repeatedly asking "Why?" to trace issues, such as Styrofoam cutting delays and rework caused by unclear drawings, back to their origins. The resulting inefficiencies were then prioritized using lean tools based on their frequency, their effect on production, and the ease with which they could be addressed.

A major source of inefficiency was the lack of standardization in product design. This led to repeated customer meetings to develop panels with specific thermal resistance (R-value) requirements. Although these customizations benefited clients, they imposed additional burdens on the company: engineers had to invest extra hours in creating unique designs, developing Revit families, and explaining the details to colleagues and production workers. These tasks increased the workload without corresponding compensation. Another technical challenge concerned rebar cutting, which often produced significant waste. To mitigate this issue, the authors developed a Python script to optimize the cutting list and reduce material waste through 1D optimization.

Overall, this paper examines issues across several stages of the manufacturing process and explains how various lean principles were applied to address them. Using the A3 problem-solving method illustrated in Figure 2, the authors first conducted a thorough analysis of the issues, then evaluated multiple alternative scenarios, and finally proposed practical countermeasures. Implementation efforts involved extensive consultations with precast plant workers, followed by feasibility assessments of each proposed solution. The engineering team was closely involved in evaluating the practicality of the recommended changes and considering alternatives when necessary. The paper concludes with planned evaluations of efficiency improvements and stakeholder satisfaction once the solutions are fully implemented.

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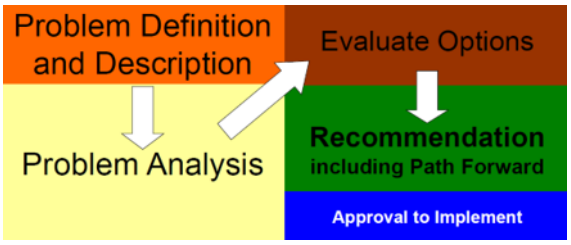


Figure 2. The Flow of the A3 Process

(Source: HerreroBoldt & Cathedral Hill Hospital Project)

Bottleneck

During the on-site observations, noticeable delays and periods of worker idle time were identified in the material preparation stage. To better understand the reasons behind this idle time, the "5 Whys" technique was applied to trace the issue back to its root cause. As summarized in Table 1, the main bottleneck originates from the Styrofoam cutting station, which creates downstream delays and idle time for other workers. This bottleneck is ultimately linked to delays within the engineering team, who must produce shop drawings without a standardized design. The absence of standardization forces engineers to prepare shop drawings and cutting lists for each individual panel rather than generating a unified set for the entire project, further compounding the delays.

Table 1: 5 Why Method

WHY:	Material preparation is not done on time
WHY:	Styrofoam cutting phase is consistently delayed
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)

Design Standardization

In precast construction, design standardization is a key lean principle that significantly improves manufacturing efficiency and product quality. However, the company's existing approach involves prolonged meetings among management, clients, and engineering representatives to develop customized designs for each project. These discussions typically focus on achieving the client's required thermal performance (R-value), whether through batt insulation or by adjusting the type and thickness of the Styrofoam.

To address this challenge and resolve the fifth "Why?" identified in the root-cause analysis, the authors met with the company's energy engineer to develop a standardized set of design options that clients can select from. This standardized system was created based on the most frequently requested R-values in past projects. Table 2 and Table 3 present the proposed Styrofoam configurations, including flat and U-shaped options, along with their corresponding R-values and recommended insulation types for both below-grade (basement) and above-grade applications.

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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 Type 1	1" x 19.5"
Below-grade	14	14	NA	EPS Type 1	3.25" x 19.5"
Below-grade	24	24	NA	EPS Type 1	8" x 18.5"
Above-grade	18	6.5	Batt 18	EPS Type 1	1" x 20.5"
Above-grade	18	18	NA	EPS Type 1	6" x 19.5"
Above-grade	22	22	NA	EPS Type 3	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"

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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.

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- 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:

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- 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 3 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 4 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".

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Consolidated cutting list- By-Shape

Family and Type	Label	Count	S Length	S Width	S Depth	S - Face Thickness	S - Side Thickness	Comment
3iPC - Styrofoam - Flat_Shape: 19 1/2" Wide	FS1	26	96 1/2"	19 1/2"		1"		
FS1: 26		26						
3iPC - Styrofoam - Flat_Shape: 19 1/2" Wide	FS2	12	72 1/2"	19 1/2"		1"		
LH1: 8								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 7" x 8" 3	LH2	3	47"	7"	7 1/2"	1 3/4"	1"	
LH2: 3								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 7" x 8" 3	LH3	2	75 3/4"	7"	7 1/2"	1 3/4"	1"	
LH3: 2								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 7" x 8" 3	LH4	2	58 1/4"	7"	7 1/2"	1 3/4"	1"	
LH4: 2								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH5	1	5"	5 1/2"	7 1/2"	1 3/4"	1"	
LH5: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH6	1	4 1/4"	5 1/2"	7 1/2"	1 3/4"	1"	
LH6: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH7	1	7"	5 1/2"	7 1/2"	1 3/4"	1"	
LH7: 1		1						
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH8	2	13 1/2"	5 1/2"	7 1/2"	1 3/4"	1"	
LH8: 2								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH9	1	17 1/2"	5 1/2"	7 1/2"	1 3/4"	1"	
LH9: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH10	1	45 3/4"	5 1/2"	7 1/2"	1 3/4"	1"	
LH10: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH11	1	64 1/2"	5 1/2"	7 1/2"	1 3/4"	1"	
LH11: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH12	1	78"	5 1/2"	7 1/2"	1 3/4"	1"	
LH12: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH13	1	90 1/4"	5 1/2"	7 1/2"	1 3/4"	1"	
LH13: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5 1/2" x 8" 2	LH14	1	92"	5 1/2"	7 1/2"	1 3/4"	1"	
LH14: 1								
3iPC - Styrofoam - L_Shape_w Nailer_w lip: 5	LH15	3	96"	5 1/2"	7 1/2"	1 3/4"	1"	

Figure 3. Consolidated Cutting List

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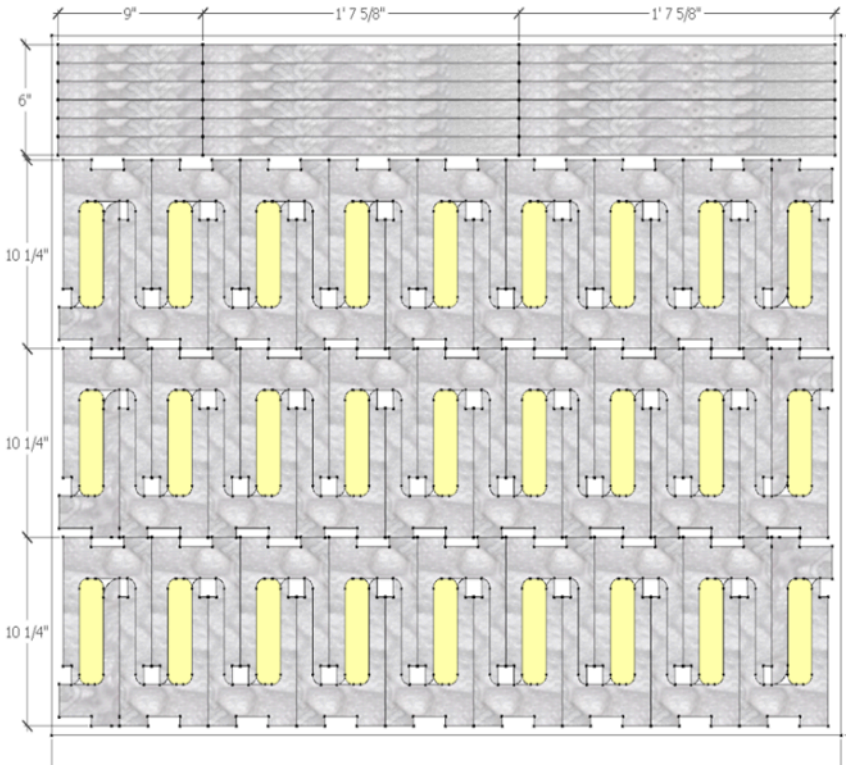


Figure 4. Optimized Cutting Pattern

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

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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 5). 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.

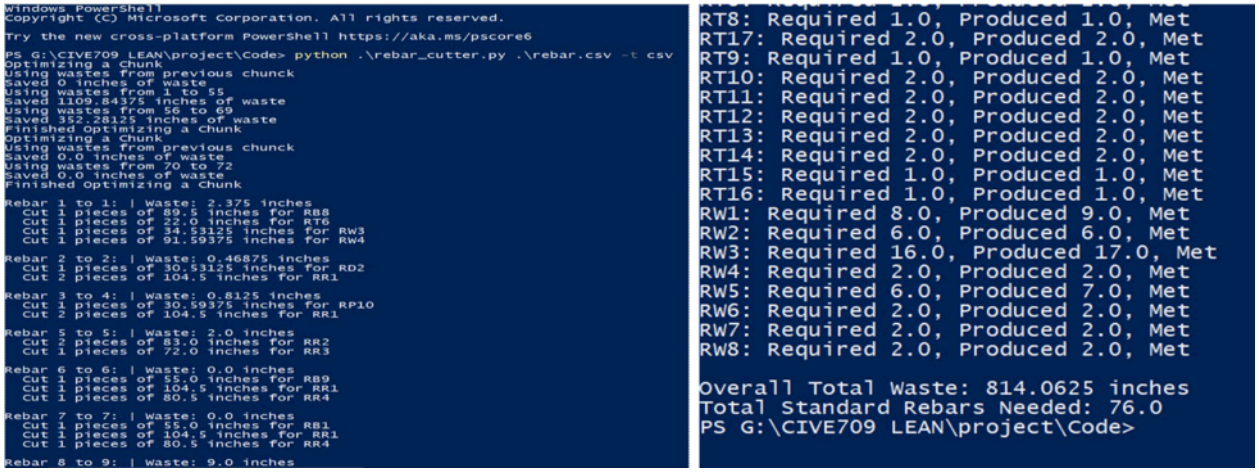


Figure 5. Rebar Cutting Instruction Sample

Discussion

This study examined how lean thinking can be used to address persistent inefficiencies in a precast concrete panel manufacturing facility. Through direct observation, worker feedback, and root-cause analysis, the research demonstrated that many performance issues, extended engineering time, production delays, rework, and material waste, stemmed from variability in design, unclear shop drawings, and the absence of a consolidated material cutting list. These findings align with established lean principles that emphasize reducing variability, eliminating over-processing, and improving workflow reliability.

A major insight from this study is the central role of design standardization in enabling downstream lean improvements. Standardizing the most common Styrofoam shapes reduced the engineering workload, eliminated repeated redesign efforts, and allowed the creation of consolidated cutting lists. This directly addressed the root cause identified through the “5 Whys” analysis: inconsistency in design was creating delays throughout the production system.

Similarly, the optimization of shop drawings highlighted the relationship between over-processing and worker confusion. Initial drawings contained excessive detail, redundant notes, and inconsistent graphical elements that forced workers to repeatedly seek clarification from engineers. Simplifying the drawings, removing non-value-adding information, and introducing colour-coding functions as a form of Poka-yoke improved communication and reduced rework. These adjustments helped eliminate Muri (overburden) for engineers and Muda (waste) in the production process while improving the reliability of information flow, an essential component of lean production systems.

The integration of a Python-based one-dimensional cutting optimization tool further demonstrated how digital tools can strengthen lean efforts. By minimizing rebar waste and

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optimizing cutting patterns, the tool supported reduced inventory waste and increased material utilization. Although many lean implementations rely heavily on manual methods, this case shows the value of combining traditional lean tools with simple computational methods to achieve more precise, scalable improvements.

In conclusion, the study reinforces that lean success depends on understanding and addressing system-level constraints rather than treating symptoms. Once the engineering phase becomes more stable and predictable, downstream processes, including Styrofoam cutting, rebar preparation, and assembly, will have a smoother flow and shorter lead times. The results highlight the importance of approaching production issues holistically, recognizing that variability in one stage can increase throughout the entire system.

Conclusion

This study applied lean principles to improve production efficiency, reduce waste, and enhance workflow reliability in a precast concrete panel manufacturing facility. The findings show that design standardization, simplified shop drawings, consolidated cutting lists, and digital optimization tools can meaningfully reduce Muda, Muri, and Mura across engineering and production activities. Standardizing common panel designs created the stability needed to reduce engineering hours. The optimized shop drawings improved communication, reduced rework, and eliminated non-value-adding tasks, while the rebar-cutting optimization tool further minimized material waste and supported more predictable production cycles.

Collectively, these interventions demonstrate that combining lean thinking with practical digital tools can significantly improve operational performance in off-site construction environments. The results also suggest that lean methodologies can be successfully adapted to precast panel manufacturing, where variability, communication gaps, and rework often disrupt production flow.

However, the findings stem from a single case within a specific organizational context. The improvements were not measured across multiple projects or tracked longitudinally. Future research could expand this work by evaluating performance across diverse facilities, integrating BIM-supported automation, or developing predictive visual management systems to further reduce variability and improve workflow reliability.

Despite these limitations, the study provides a practical roadmap for precast and modular manufacturers seeking to enhance productivity and reduce waste. By focusing on standardization, visual clarity, and simple digital optimization, organizations can strengthen their lean implementation and move toward more efficient, reliable, and sustainable production systems.

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