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MINIMIZING REWORK IN OFFSITE CONSTRUCTION: ERROR PROPAGATION ANALYSIS AND QUALITY CONTROL

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ABSTRACT

Offsite construction (OSC) is increasingly used to enhance productivity, quality, and schedule reliability through industrialized, standardized production processes. However, OSC systems remain susceptible to local execution errors that propagate across interconnected production stations, resulting in rework, delays, and waste. This research examines error propagation within an off-site wall manufacturing line by applying lean principles and techniques. An explanatory case study methodology integrates both qualitative and quantitative approaches. Gemba walks, and a Five Whys root cause analysis was conducted to identify recurring quality defects at stud locations where nails were missing. Subsequently, statistical analysis compared design and as-built dimensions of wall panels to quantify absolute and percentage errors originating from framing and nailing operations. The cumulative impact of these errors was assessed against allowable tolerance limits to determine the likelihood of defects at downstream stations. Findings demonstrate that minor geometric deviations introduced at upstream stations accumulate and surpass tolerance thresholds, substantially increasing defect rates as production advances. These results underscore the necessity of quality-at-the-source practices and intermediate quality checks in OSC systems. This study advances lean construction knowledge by providing empirical evidence of station-level error propagation and recommending targeted remedial actions to improve production flow stability and built-in quality.

KEYWORDS

Offsite construction, lean production, error analysis.

INTRODUCTION

The construction industry is moving away from traditional on-site methods and adopting more industrialized off-site production systems. McKinsey & Co. (2020) reported Offsite Construction (OSC) as a method for improving construction process productivity. Off-site construction, also known as industrialized, prefabricated, or modular construction, involves manufacturing building components in a factory and then bringing them to the site for assembly (Goodier & Gibb, 2007). By performing the work in a controlled environment, labor and material consumption are minimized, thus improving productivity, quality, and schedule

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reliability (Quale et al, 2012). The standardization in OSC also fits well with lean principles, which focus on increasing value by minimizing variability and waste. However, OSC systems can still face production problems (Koskela, 2002). Small mistakes, geometric errors, or process inconsistencies can have a domino effect on upcoming operations. So, it is important to understand how these local errors start and spread through the production process to keep processes running smoothly and increase the value generation.

In OSC, building components such as walls, floors, beams, or roofs flow through a sequential interconnected set of stations, each adding value to the final product (Prado Lujan, 2022). When applying standardized work procedures, clear process sequences, and good coordination between upstream and downstream operations help keep lean production running smoothly (Zaalouk et al., 2023). In this system, each production station effectively functions as an internal customer of the previous one. Each station depends on the quality and completeness of the incoming work to perform its tasks successfully (Khalife & Hamzeh, 2020). From a lean perspective, value is realized only when work is delivered to the subsequent process in a condition that meets specified quality standards (Ballard, 2001).

As Dr. Deming stated, "Variability is the enemy of quality" (Hunter &Bellows, 2018). In construction, projects come in many sizes and face different conditions, leading to variability driven by customization, changing requirements, or a lack of standardization. Even in off-site building processes, customer needs and choices vary—such as variations in wall type, size, or features—which create execution challenges. The different specifications of elements increase the process's variability over time and make it harder to control. Unevenness or variability in production, referred to as "Mura" in Japanese (Shook, 2007), can contribute directly to the 8 types of waste identified by Ohno (Gupta et al., 2025). Inconsistency can trigger rework, delays, overprocessing, or other forms of waste as identified in the Toyota Production System (Liker, 2004).

In the Toyota Production System, built-in quality, also known as "Jidoka" in lean terms, refers to looking for mistakes after each step and fix it at the spot, instead of letting it move down the line (Liker, 2004). If waste (or errors) slip through, they can disrupt the workflow, cause rework, lower the quality, and reduce the value delivered (Shehab et al, 2025). Minor avoidable errors made early in the process can lead to bigger problems and later downstream. While implementing continuous quality checks at every station is widely recognized in lean theory for preventing defect propagation and minimizing waste (Rasouli, 2025), it is often difficult to put into practice. Many production lines are simply not set up for it. Manual tasks are more likely to go off track compared to digital ones (Alsakka et al, 2023), but on the other hand, it can be tough to spot mistakes quickly at tightly coupled automated stations (Lui et al., 2022). If issues like geometric deviations or misplaced fasteners or nails are not caught and fixed early, the following stations must spend extra time and effort making up for it, which leads to more waste and less efficiency (Lei et al, 2023). Since every station in OSC depends on the one before it, a single mistake can snowball and affect the entire production line, making the system less reliable overall (Attajer &Mecheri, 2024).

Reviewing the body of knowledge for studies addressing error propagation and quality control in construction reveals interesting insights. While several researchers have looked at these topics in construction, there is still a gap in understanding how they work at the station level in off-site construction (OSC) environments. Hasan and Lu (2021) developed an error-propagation model for industrial construction to analyze labor cost budget risks and to demonstrate the financial impact of undetected errors. Moreover, Botchway & Pan (2022) studied quality in OSC at the system level. They aimed in their study to quantify rework at the end of the process. Lui et al. (2022) also gave a broad overview of quality control practices in OSC, focusing on inspection controls, digital monitoring, and following standards. However, their findings show that quality control is mostly based on product checks and final inspections,

not as a continuous process at each station. To help with more targeted quality checks, Martinez et al. (2019) introduced a BIM-based tool for automatically selecting quality control specifications for off-site manufactured products. While this tool clarifies what should be monitored at each station, it does not provide data on how specific errors move to later workstations.

To address the existing knowledge gap regarding station-level error propagation in OSC, this paper presents a framework to detect local geometric deviations accumulated across interconnected automated workstations. Specifically, the paper aims to: (1) investigate the root causes of manufacturing deviations using lean techniques, (2) quantify how local execution errors propagate to downstream stations, and (3) provide targeted remedial strategies to enhance production flow stability and Jidoka. The study shifts the focus from traditional end-of-line product inspections to continuous, station-level quality control.

The paper is organized as follows: The upcoming section explains the methodology followed for the study and the methods performed. This is followed by the case study context and research methods used to collect and analyze data on nailing errors and their downstream effects. The results of the study are analysed and discussed in terms of their implications for lean improvement and built-in quality in OSC. Finally, a conclusion is drawn to summarize key findings, outline limitations, and propose directions for future research.

METHODOLOGY AND METHODS

An examination of the research questions indicates that a case study research strategy is appropriate for this investigation. Case study research is particularly suitable for addressing how and why questions within contemporary, real-world contexts where the researcher has limited or no control over behavioral events (Yin, 2003). This approach enables an in-depth examination of complex phenomena as they occur in practice. Furthermore, case studies support the integration of qualitative and quantitative methods to explain observed processes and outcomes (Hamzeh, 2009). They allow for the analysis of causal relationships through empirical, real-life evidence and provide rich observational insights to identify and evaluate underlying mechanisms. The use of multiple sources of evidence within a natural setting also facilitates rigorous data triangulation, strengthening the validity of the findings (Hamzeh, 2009).

By capturing the temporal and contextual dimensions of production activities, the case study methodology enables a detailed understanding of process dynamics and variability, thereby supporting robust analysis and interpretation of results (Meredith, 1998). Accordingly, this study adopts an explanatory case study approach to investigate the root causes of quality deviations and variability within a wall manufacturing production line, and their effects on the production process.

The methodology framework is illustrated in Figure 1. The process starts with Gemba walks on the shop floor to observe the wall manufacturing line and understand how the process is carried out. It also helped in building contextual knowledge for the study. After that, a hypothetical cause is developed after investigating the observed defects using the root cause analysis Technique, especially 5 whys. The team focuses on investigating geometric characteristics and recurring patterns of defects. Based on that, a statistical analysis is performed by comparing the design dimensions and the actual dimensions of the panels to calculate the error and the percentage error. Primary data was collected on-site. Finally, the results were verified and validated by comparing them to the allowable tolerance limits. Once the root cause is identified, remedial solutions are proposed to address the source of quality deviations. These solutions aim to improve quality at the source and reduce the occurrence and propagation of defects across subsequent production stations. The proposed actions are evaluated in terms of their potential impact on process stability and production efficiency.

Upon identifying the root cause of the observed defects, targeted remedial solutions are proposed to improve production quality and reduce defect propagation within the manufacturing process.

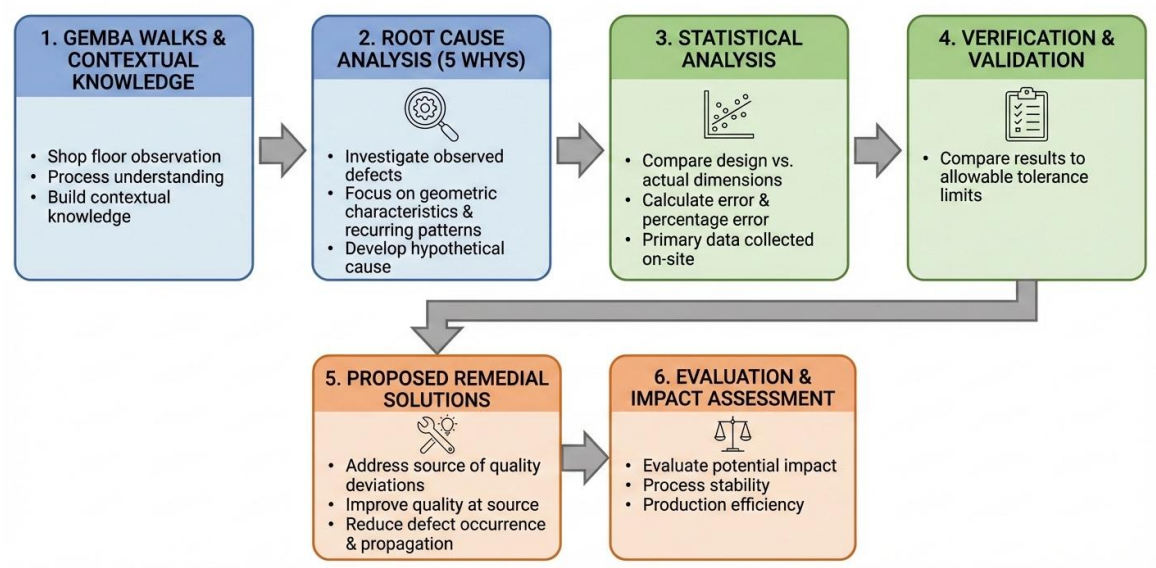


Figure 1: Methodology framework

CASE STUDY

PROCESS AND PROBLEM DESCRIPTION

The case study was conducted at an OSC manufacturing facility that produces residential building elements, including walls, roofs, stairs, and floor decks. Among the various production lines, the wall manufacturing line was selected for this study due to the recurring quality issues and rework observed during daily operations. These issues made the wall line a suitable case for investigating error propagation within an OSC environment.

The manufacturing line for walls is made up of several sequential stations. When the order is initiated, the frame of the wall is built at the framing station. The work is semi-automated, where a worker pulls studs and feeds them to the machine. The machine shoots nails based on a design drawing. When the frame is constructed, it moves on a conveyor belt onto the sheathing tables. In this stage, 2 workers are assigned to place sheaths on the wall panel manually. The workers staple the wall to prevent it from dislocating when the panel is conveyed. After that, the wall panel goes through a multifunctional bridge where the nailing process is performed. This process is fully automated once the operator confirms the wall name and nailing pattern associated with it. The bridge automatically shoots nails and performs coring in case the wall includes an opening. The wall panel is flipped vertically with the aid of a “butterfly rotation table”. The butterfly table allows the flip of the panel from horizontal to vertical alignment. The wall is then moved into the first quality check stop, where it is examined for defects. Finally, the wall moves into the doors and windows station where aluminium works are performed. Finally, it got loaded onto trailers at the loading bay and sent to the site for installation. Figure 2 illustrates the sequence of stations.



Figure 2: Wall manufacturing process flow

Upon reaching the quality check station, a significant number of walls exhibit two distinct types of defects: nails missing the studs (Stud rupture) and nails not shot (Missing nails). These defects are causing operational disruptions and increasing rework efforts. Also, when the nails are shot out of the studs, it is risky for workers to install the insulation as they can cut their hands with the sharp nails. Figure 3 illustrates the defects the study aims to diagnose. The team labelled them Problem A and Problem B, respectively. The case study will examine the cause of Problem A.

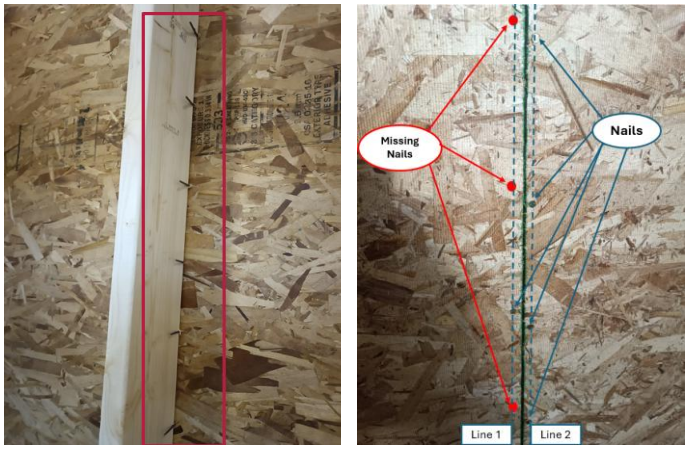


Figure 3: (a) Problem A: Stud rupture, or nails shot out of the stud; (b) Problem B: Missing nails

DEFECT PATTERN AND ROOT CAUSE ANALYSIS

The defects are detected at the quality check stop. This action happens after 3 main stations: (1) the framing station; (2) the sheathing station; and (3) the multifunction bridge or nailing station. Since the wall is placed horizontally as shown in Figure 4, the problem could not be detected. Thus, Quality at Bay could not be applied, as the case study was not relevant to the research problem.



Figure 4: Wall panels placement in the sheathing and nailing stations

The team examined the defect pattern and the frequency of its occurrence. We noticed that in most walls, the nails were shot just before the stud, though there were rare cases where they were shot after the stud. Also, the team noticed that, in most cases, nail deviation is increasing; in other words, as the number of studs in a wall increases, nails are shot farther from the designed line.

The defect pattern raised several questions, but still, the main question is *Why is this happening?* The journey to identify the root cause began by requesting the design drawings to ensure there were no issues with the design and specs. After examining the design drawings, we found nothing wrong with the design.

The Five Whys analysis was conducted by repeatedly asking why nails were missing from the studs, based on direct observations from Gemba walks and measurements collected on the production line. Each "why" iteration focused on progressively deeper causes, moving from the visible defect to upstream process conditions, including work methods, station layout, and interactions between consecutive production stations. This iterative questioning process enabled the identification of the root cause responsible for the recurring defect pattern.

The question was: Why is there rework? Why are nails shot out of the studs? Why does the nail defect pattern recur? Which station is responsible for the error? Why? Why, etc., the sequence of questions asked is illustrated in Table 1 to describe the Root-Cause analysis. Trials and Iterations were performed to verify the causes by going on the shop floor and examining the predicted cause.

Table 1: Root cause analysis using the 5-whys technique

Why Level	Observation
Why 1	Rework, delays, and overprocessing occur due to quality defects.
Why 2	Quality defects occur because nails are shot outside the stud locations.
Why 3	Nails miss studs because the nail line deviates beyond allowable tolerances.
Why 4	Nail line deviations result from execution errors during upstream operations.
Why 5	Execution errors accumulate due to the absence of quality-at-the-source checks between framing and nailing stations.

The Five Whys analysis revealed that the observed defects were not caused by isolated execution errors but by the accumulation of geometric deviations originating in upstream stations, particularly in framing and nailing operations. The absence of intermediate quality

checks allowed these deviations to propagate downstream, resulting in nails missing studs and triggering rework, delays, and overprocessing.

STATISTICAL STUDY

The team wanted to verify the qualitative diagnosis of the problem through a quantitative statistical study to calculate absolute and percentage errors. The absolute error is the difference between the designed and executed locations, while the percentage error indicates how far the item (nail or stud) was from the designed location. Both metrics will help the team analyse the geometrical deviations and verify the hypothesis. A random sample of 20 walls was selected for the study.

Framing Station Error

Studs are typically placed every 63.5 cm (approximately two studs per 127 cm wide sheathing panel). At intermediate studs, a single line of nails is fired into the center of the member, providing a wide margin for error. In this study, we focused specifically on the Joint Studs, the members located at the interface of two sheathing panels. The team measured the distance between the joint studs and compared it to the design drawings. The difference between the two was labelled as the framing error since it is generated at the framing station. The measurement was performed manually for each sample. The walls in the sample ranged between 3 and 5 meters long, thus, having 4 to 6 studs. Following the design criteria drawings, which indicate the distance from each stud relative to the initial point of the wall, the team measured this distance. It fitted the data into a normal distribution. The positive value indicates that the deviation is occurring farther from the desired location, while the negative sign indicates it is occurring closer to the beginning. The normal distribution of each student is shown in Table 2.

Table 2: The mean and standard deviation for framing error for each stud (Just after)

Stud	Mean (cm)	$\sigma_{framing}$
Stud 1	0.121	0.1566
Stud 2	0.19	0.2
Stud 3	0.21	0.244
Stud 4	0.2	0.187083
Stud 5	0.46	0.545894
Stud 6	0.4	0.141421

Nailing Error

The nailing error represents the deviation occurring at the multifunction bridge station. According to the design, nails are placed at stud locations where the sheathing is connected: two nails are driven at joint studs, while one nail is placed along each edge. To quantify the nailing error, manual measurements were taken to determine the actual nail positions relative to their intended locations. Observations showed that, for joint studs, one nail was consistently driven within the stud, while the second nail was often misplaced outside the stud. Therefore, the deviation of the misplaced nail was considered for analysis, and its mean and standard deviation are presented in Table 3. An illustration of the nailing configuration is provided in Figure 3(b) for clarity.

Table 3: The mean and standard deviation for nailing error for the second nail at each stud

Stud	Mean (cm)	$\sigma_{nailing}$
Stud 1	0.055556	0.181046
Stud 2	0.222222	0.156347
Stud 3	0.166667	0.173205
Stud 4	0.111111	0.236878
Stud 5	0.055556	0.187824
Stud 6	0.155556	0.218581

Allowable Tolerance

The allowable error (tolerance) was calculated based on the nailing pattern given to the machines. The stud width used in the design was 38mm. Since 2 nails are placed on each stud, the distance was divided in half, where each half is assigned to a nail. In the nailing pattern, the distance from the panel edge and from the stud edge to the nail centerline is 8mm each. Therefore, by removing the edge distances to the timber edge and board from the stud width, the tolerance becomes as follows:

$$\text{Tolerence} = 38/2 - 8 - 8 = 3\text{mm}$$

Further analysis and research were conducted to determine the minimum nail cover. According to McVicker (2013), nails should have an edge distance of at least 6mm in practice. This measurement provided 2mm extra, bringing the tolerance to 5mm in total.

Total Error (or Built-up error)

The framing error and the nailing error were added to form the total error. At each stud location, random cases were generated to populate the data for the total error based on generic random numbers. The generated random numbers are used to calculate the framing and nailing error. The values were added to calculate the built-up error for each instance. 200 points were estimated using the mean and standard deviation for every location. The total error values were fit into normal distributions as shown in Figure 5. The mean and standard deviations for each distribution are represented in Table 4.

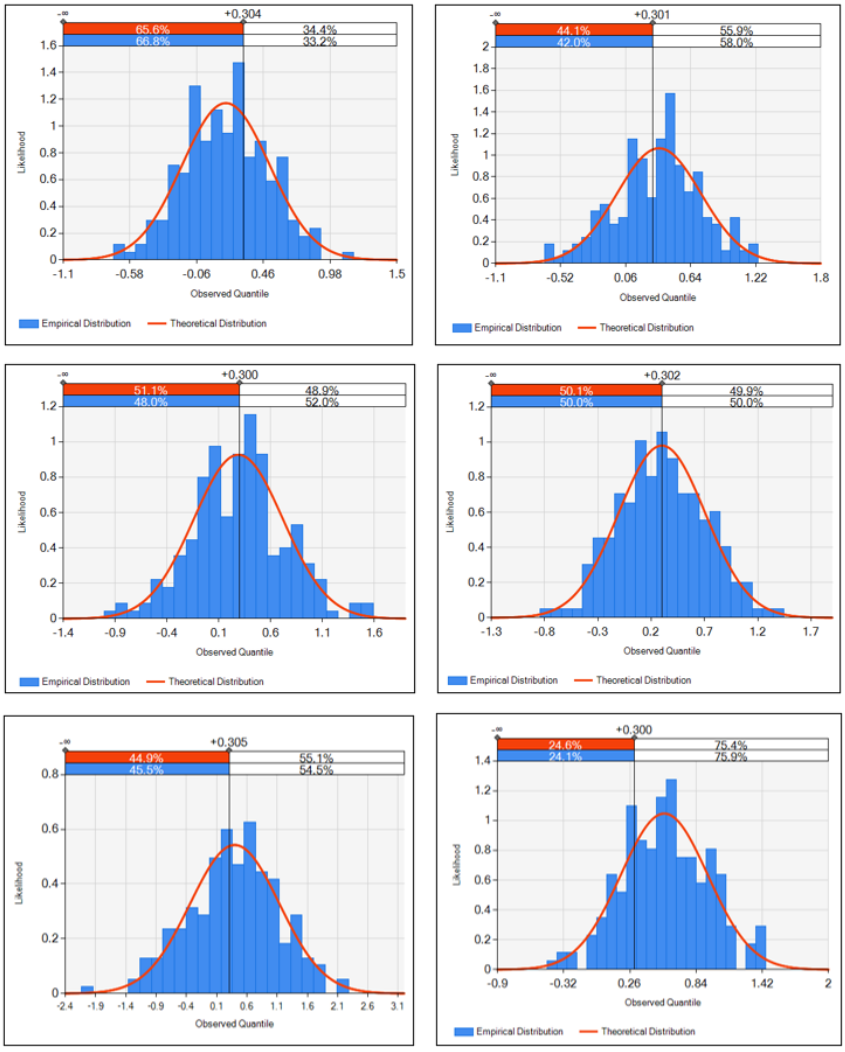


Figure 5: The distributions at every stud location starting from stud 1, stud 2, stud 3, stud 4, stud 5, and stud 6.

Table 4: Probability distributions for each stud location, along with the probability of being within the acceptable range.

Stud Location	Error	P(X≤0.3cm)	P(X≤0.5)	Defects %
1	Norm (0.16, 0.34)	65.6%	83.80%	16.2%
2	Norm (0.456, 0.36)	44.1%	65.20%	34.8%
3	Norm (0.288, 0.43)	51.1%	69%	31%
4	Norm (0.3, 0.4)	50.1%	69%	31%
5	Norm (0.4, 0.736)	44.9%	55%	45%
6	Norm (0.561, 0.381)	24.6%	44%	56%

Material Quality

Studs were measured to verify consistency between actual and design dimensions. 3 dimensions were taken from each stud (Top, bottom, and middle). 50 studs were measured, and the actual dimension was calculated as the average to be 36.4mm (1.6mm less than the design dimension). Material storage conditions play a critical role in maintaining the dimensional accuracy of wood

studs. As per the stud's manufacturer specifications sheet, the Moisture content should be below 10%, which must be maintained throughout storage and handling. Deviations from these conditions, such as outdoor storage or exposure to moisture, can alter the moisture content of the wood, thus affecting the dimensional consistency of the material. Figure 6 represents a wall section with a bent stud installed in it.

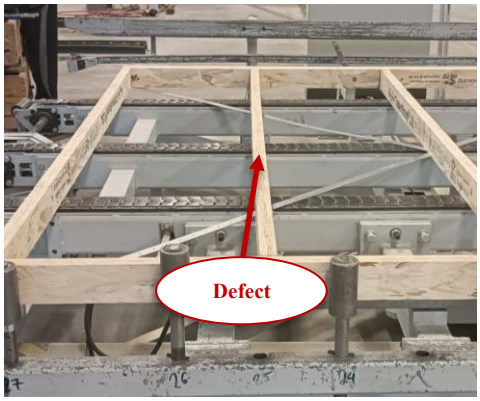


Figure 6: Defected bent studs

DISCUSSION

The main objective of the case study was to demonstrate how errors are transferred and accumulated along the stations of the OSC lines and to highlight the importance of *Jidoka*. The statistical case study between the design and as-built measurements showed that errors can snowball and amplify if not addressed promptly. The root cause analysis indicated that the primary source of defects was not design-related but process-related, specifically the absence of quality-at-the-source mechanisms at upstream stations.

In addition, the statistical study helped in quantifying the errors. By separately calculating the deviations caused by the framing and the nailing machine, we concluded that both contributed to the problem, especially when they shift in the same direction. Moreover, the statistical study showed that the likelihood of nails being shot outside the stud increases with wall length as the number of studs increases. This theory was proved in Table 4, which showed that the % defects increased exponentially up to "stud 6".

As both stations are automated, the error can be attributed to a machine-related issue rather than human error. The tolerance for nail misplacement is set at 3 mm, which is likely insufficient. Furthermore, the design specified a stud thickness of 38 mm, but measurements indicate a mean thickness of 36 mm. This discrepancy reduces the effective tolerance for each nail by an additional 1 mm, bringing the total tolerance to 2 mm.

While previous studies have primarily assessed variability and defects at a downstream or system level (Botchway &Pan, 2022; Lui et al, 2022), this framework enables the monitoring and quantification of deviations at the station level. This finer level of analysis allows for the identification of error sources at specific production stages, rather than treating the process as a black box. Consequently, it supports early detection and immediate correction at each station, which are critical to maintaining stable flow and consistent quality. These findings further reinforce the role of *Jidoka* as a key lean principle for controlling variability in OSC.

Based on that, we provided several suggestions to the management to minimize the errors. The first suggestion was to provide additional restrictions on material control to ensure that the received studs and panels comply with the specs. We also proposed shifting the nailing pattern by a distance equal to the mean total error. Simulation results show defect reduction consistent with Table 5, improving quality but not eliminating error risk.

Table 5: Probability of no defects based on the adjusted nail location.

Stud Location	Average error (cm)	Adjusted Tolerance (cm)	No defects Chance
1	0.16	0.66	93%
2	0.45	0.95	98%
3	0.288	0.788	88%
4	0.3	0.8	89%
5	0.4	0.9	75%
6	0.56	1.06	90.50%

CONCLUSION

While this research utilizes a single wall-manufacturing line as an explanatory case study, the primary contribution to the advancement of knowledge is providing a replicable methodology framework to quantify the snowball effect of geometric tolerances in OSC. Lean tools, including a Gemba walk, root cause analysis, and statistical comparison of design and as-built dimensions, were used to investigate the source of defects. The results showed that small upstream deviations can snowball into major quality problems when quality-at-the-source is not applied. By demonstrating how framing and nailing errors interact and intensify, the case study offers practical evidence that variability disrupts production flow and increases waste.

Despite these contributions, this research has some limitations. The analysis is limited to a single production line with a specific wall configuration. Additionally, the findings are based on a restricted dataset and focus exclusively on geometric deviations, not accounting for other potential defect types such as material degradation or environmental factors.

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