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# COMPARATIVE ANALYSIS OF CONSTRUCTION WASTE: ROBOTIC VS. MANUAL OFFSITE ASSEMBLY

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## ABSTRACT

Construction waste (CW) is a significant environmental concern that started to shape the future of the construction industry. Offsite construction (OSC) is one key approach widely praised for its capability to reduce CW due to its controlled environment where lean and technology principles can be applied. Despite the growing research confirming OSC capability to promote productivity and reduce lead times, evidence on material efficiency is highly limited. Hence, this study aims to fill this gap in the literature by conducting a comparative case study to investigate CW generation in OSC. Two timber frame panelised construction factories were approached with OSB assembly stations chosen to investigate how, how much and why CW is generated and whether lean and technology uptake are supporting CW reduction. While Factory A adopted a manual station to assemble the OSB layer, Factory B adopted a fully automated robotic station. The results indicate that the robotic station generated significant offcuts, accounting for 27% of the total OSB usage, compared to 16% generated by the manual station. The application of lean and technology practices is found to primarily focus on workflow, time, and cost, with limited consideration to material efficiency.

## KEYWORDS

Construction Waste, Offsite Construction, Lean Construction, Automated Assembly

## INTRODUCTION

The construction industry is a major contributor to solid waste, generating over one-third of the global solid waste figures (Sivashanmugam et al., 2023). One key justification to the wasteful trend in construction is the traditional stick-built approach, that is known for its limited standardisation and automation (Li et al., 2014). In response, several global initiatives being promoted to reduce construction waste (CW), including offsite construction (OSC), which involves prefabricating required construction components in a factory before transporting them to the construction site for final assembly.

Thanks to the controlled environment seen in OSC, growing literature promoted the uptake of production-like principles and technologies. This includes the employment of lean principles of 1) value stream mapping (VSM) to reduce production lead times (Ayinla et al., 2022; El Sakka et al., 2016), maximise productivity (Goh & Goh, 2019; Yu et al., 2013), and lower costs (Heravi & Firoozi, 2017; Laika et al., 2022), 2) just-in-time (JIT) to promote collaboration

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between offsite production and onsite assembly teams (Peñaloza et al., 2016; Salama et al., 2021), and 3) batch size reduction to encourage design modularisation and standardisation (Choi et al., 2020; Feist et al., 2022).

Similarly, several studies investigated the use of a range of digital technologies as enablers to lean application in OSC. This includes the adoption of 1) 4D BIM to promote cross-team interoperability necessary to synchronise JIT production-logistic processes (Bataglin et al., 2017, 2020; Bortolini et al., 2019), 2) IoT tracking to support real-time product visibility (Wang et al., 2020; Xu et al., 2018), 3) optimisation algorithms to modularise design into smaller components that can be manufactured offsite (Feist et al., 2022), and 4) discrete event simulation to model and optimise the production process in pursuit of continuous improvement objectives (Afifi et al., 2020; Barkokebas et al., 2021; El Sakka et al., 2016).

Hence, these studies have investigated the uptake of a range of lean principles and technological enablers mainly to optimise lead times, productivity, and cost. However, limited research employed lean or technology principles to optimise CW in OSC (e.g., Gbadamosi et al., 2019). One possible explanation is the lack of empirical research that investigates how, how much, and why CW is generated throughout the production process of OSC products. Existing studies (Jaillon et al., 2009; Lu et al., 2021) have been conducted at macro level, where CW is quantified at project level with no further analysis provided at activity level. In addition, many of these studies were either based on secondary data, derived from industry average (Hao et al., 2021; Hernández et al., 2023; Loizou et al., 2021; Mirshekarlou et al., 2021) or subjective data collected from questionnaires (Eghbali et al., 2019). Thus, no study was conducted to investigate CW generation in OSC using direct observations.

To fill this void in the literature, direct observations were conducted at two OSC factories to investigate construction waste generation. This method is essential for capturing activity-level waste-generating practices in different production environments: Factory A (manual station) and Factory B (fully automated robotic station). By observing real-time operations, this study ensures an empirical understanding of waste sources. Furthermore, the lean principle of the 5 Whys was applied to uncover the root causes behind these waste-generating practices, rather than settling for surface-level explanations. This approach strengthens the study's ability to explain how, how much, and why CW is generated in OSC, while also evaluating whether current lean and technology applications contribute to material efficiency.

# METHODOLOGY

The purpose of this research is to investigate CW generation in OSC across manual versus fully automated prefabrication stations. Particularly, this study attempts to answer questions on how, how much, and why CW is generated in OSC and whether the current level of lean and technology application is contributing to CW reduction. To answer these questions, two OSB assembly stations were investigated across two OSC factories producing timber frame panelised construction products (e.g., walls, floors, ceilings). Factory A uses a manual station, whereas Factory B relies on a fully automated station. The following subsections describe each assembly station in more detail:

## MANUAL STATION

This station relies on the physical input of workers to measure, cut, fit, and nail the required OSB pieces. Observations at this station covered 12 wall panels over the course of three working days to closely monitor OSB assembly activities. Initially, two stocks of standard OSB board sizes—2400 x 1200 mm and 2700 x 1200 mm—are placed near a wall saw. The saw operator then measures and cuts the required OSB pieces based on the shop drawings, on a panel-by-panel basis. Simultaneously, the operator manually labels the cut pieces, groups them by panel, and places them along with their corresponding shop drawings in a steel stillage. The stillage is then transported to the OSB assembly station, where the required pieces are fitted and nailed into their designated positions according to the shop drawings. Figure 1 illustrates the sequence of activities followed at the manual OSB assembly station.

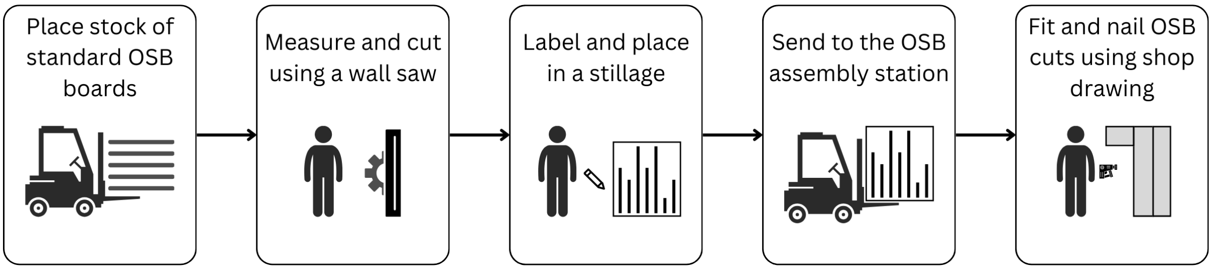


Figure 1: Process Activities - Manual Assembly Station

## AUTOMATED STATION

This station is operated by robotic arms capable of picking, fitting, nailing, and cutting boards in accordance with the shop drawings. Observations at this station covered eight wall panels over the course of two working days to closely monitor OSB assembly activities. Initially, two custom-sized OSB boards (597 x 1200 mm and 797 x 1200 mm) and one standard-sized OSB board (2400 x 1200 mm) are regularly placed in their designated positions near the robotic arms. Based on a predetermined configuration designed for each wall panel, the robots are programmed to perform the assembly tasks. This includes selecting one of the three OSB sizes as needed and fitting it into its specified position on the frame. Once all required OSB boards are in place, the robotic arms automatically switch to nail guns to secure the boards. They then switch to electric saws to trim excess OSB along the panel edges and over the openings (e.g., windows and doors). Figure 2 illustrates the sequence of activities followed at the automated OSB assembly station.

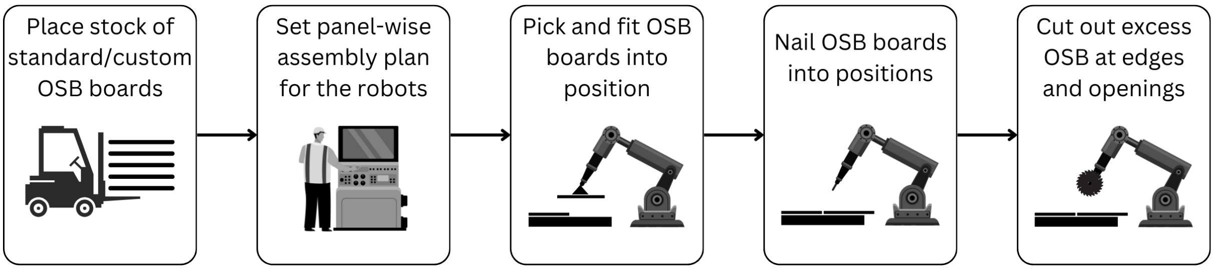


Figure 2: Process Activities – Automated Assembly Station

Hence, OSB assembly activities across the abovementioned production stations were observed primarily to investigate the practices, quantities, and root causes of the CW generated in OSC and whether lean principles and technological enablers are properly employed to reduce CW. Different from previous studies that failed to provide micro level analysis of CW, this study adopts activity-level direct observations to understand the practices and quantities and their root causes, both in manual and automated approaches. The choice of the factories was made purposively to ensure different levels of automation for the same material assembly activities.

To enhance the credibility and reliability of the research, direct observations were supplemented with interviews and documentary analysis. Three semi-structured interviews, each lasting 20–30 minutes, were conducted with production, procurement, and design managers at each factory. Follow-up interviews were conducted to validate the initial findings and reconcile any potentially conflicting results. In addition, design documents for the observed panels were requested and analysed to support a more accurate understanding and calculation of quantity take-offs and the CW generated. Table 1 outlines the data collection methods employed and their specific purposes.

Table 1: Adopted Data Collection Methods and their Use

| # | Data Collection Method | Used for |
|---|---|---|
| 1 | Direct Observations | To understand how and how much CW is generated during OSB assembly activities. |
| 2 | Interviews | To validate the observations and identify the root causes behind CW generation |
| 3 | Design Analysis | To understand the design practices and calculate the material quantities required |

# RESULTS

The collected data from the observations, interviews and documents were then analysed to identify the practices, quantities and root causes of CW across the two OSB assembly stations:

## MANUAL STATION

Based on the shop drawings for the 12 wall panels observed at this station, the required net area of the OSB layer was 241.63 $m^2$. In comparison, direct observations showed that 286.2 $m^2$ of OSB was actually used, resulting in 44.56 $m^2$ of waste, approximately 15.6% of total material use. This waste can be classified into three categories:

### Length-side OSB Offcuts

These offcuts were generated from cutting 115 mm strip from the 2700 mm side of the OSB boards (i.e., the length-side), contributing to 5.6% of total OSB use and 36% of the total OSB waste (see Figure 3). To identify the root cause behind this offcut generation, the lean principle of 5 Whys was applied during the interviews and is presented in Table 2 below.

Table 2: Length-side OSB Offcuts - Root Cause Analysis

| # | Why Questions | Justification |
|---|---|---|
| 1 | Why were 115 mm offcuts generated from the 2700 mm side of the OSB boards? | Because the panel height requires a 2585 mm OSB cut, which is 115 mm shorter than the 2700 mm OSB length. |
| 2 | Why was the wall panel height designed at 2585 mm? | Because design customisation is prioritised over standard material size consideration. |
| 3 | Why was the 2700 mm OSB boards sourced? | Because the 2700 mm OSB is the closest standard size in the market that yields the least offcuts. |
| 4 | Why wasn't a custom-size OSB considered to reduce these offcuts? | Because custom-size ordering is costly and entails longer lead-time to source. |

Hence, the root cause for the 115 mm offcuts generation is the limited consideration to the standard material size and the prioritisation of design customisation. Although souring custom-size OSB boards can eliminate these offcuts, the associated higher cost and longer lead-times make this option less feasible. Figures 3 and 4 illustrate the 115 mm offcuts.

### Width-side OSB Offcuts

These offcuts were produced from cutting different widths from the 1200 mm side of the OSB boards (i.e., the width-side), contributing to 6.6% of the total OSB use and 42% of the total generated OSB offcuts. To identify the root cause behind this offcut generation, the lean principle of 5 Whys was applied during the interviews, as presented in Table 3.

Table 3: Width-side OSB Offcuts - Root Cause Analysis

| # | Why Questions | Justification |
|---|---|---|
| 1 | Why were significant amount of width-side OSB offcuts generated? | Because of the limited design optimisation to the OSB cuts required. |
| 2 | Why was not OSB design optimised to enhance material efficiency? | Because of the automated design tool that auto-generate ranges of OSB width cuts. |
| 3 | Why did the design tool randomly generate in-range OSB width cuts? | Because the design tool is not trained to integrate different cuts, handling each cut separately. |

Therefore, the design tool's limited ability to integrate various OSB width cuts is a root cause of excessive width-side offcut generation. For instance, standardising cuts into three groups (e.g., quarter, half, and two-thirds of a board) can improve material efficiency and speed up cutting. Figure 5 shows the stored width-side OSB offcuts intended for future reuse.

Figure 3: Length-side OSB Offcuts

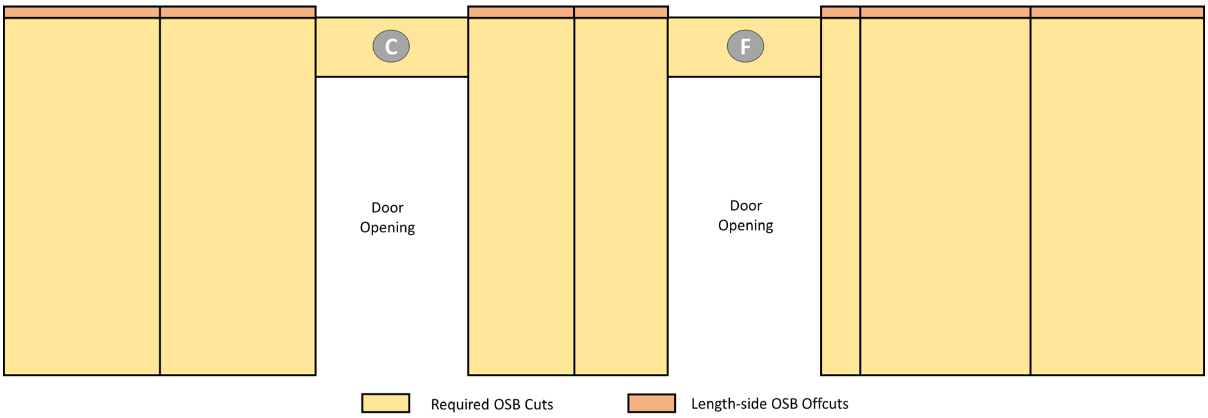


Figure 4: Required OSB Cuts and Length-side Offcuts – Sample from the Manual Station

**Filler OSB Offcuts**

These offcuts were generated from the need to produce various filler cuts to cover the door and window headers (see sections C and F at Figure 4). These offcuts contribute to nearly 3.3% of total OSB use and 21% of the total generated OSB offcuts. To investigate the root cause of this offcut generation, the 5 Whys technique was employed as part of the interviews, with the findings presented in Table 4:

Table 4: Filler OSB Offcuts - Root Cause Analysis

| # | Why Questions | Justification |
|---|---|---|
| 1 | Why were filler OSB offcuts generated? | Because of the unstandardised cut size design of the door and window header areas. |
| 2 | Why was no cutting optimisation applied across different panels to reduce offcuts? | Because of the need to cut on panel-by-panel basis |
| 3 | Why was the OSB being cut on panel-by-panel basis? | Because of the need to keep the production line fed with needed OSB cuts. |

Therefore, due to the clear prioritisation of productivity, the required cuts for the door and window headers were cut on panel-by-panel basis to keep the production line fed with needed cuts on time. However, this prioritisation of production flow comes at the expense of material efficiency, as cross panel cutting optimisation was not conducted.

Figure 5: Width-side OSB Offcuts being Stored aside

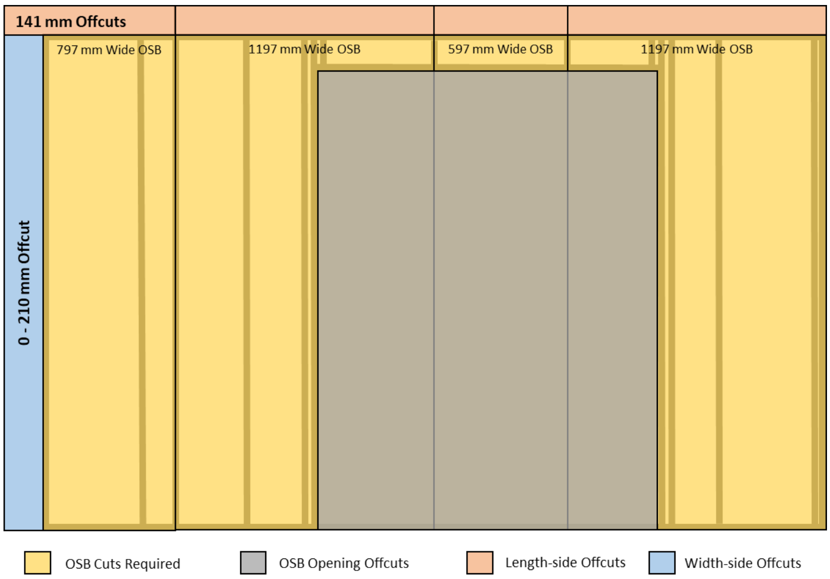


Figure 6: Required OSB Cuts and Generated Offcuts – Sample from the Automated Station

## AUTOMATED STATION

Based on the drawings provided for the eight panels observed at this station, the total required area of OSB boards was calculated to be 56.54 m$^2$. In comparison, the total quantity of the used

OSB boards was calculated at 76.96 $m^2$. This means that the total OSB waste generated is 20.42 $m^2$, making about 27% of the total OSB use. This waste can be categorised into three categories:

**Length-side OSB Offcuts**

These offcuts were generated by the robotic saw from cutting 141 mm strip from the 2397 mm side of the OSB boards, contributing to 6% of total OSB use and 22% of the total OSB waste (see the light red strip at Figure 6). To identify the root cause behind this offcut generation, the lean principle of 5 Whys was applied during the interviews, as detailed in Table 5.

Table 5: Length-side OSB Offcuts - Root Cause Analysis

| # | Why Questions | Justification |
|---|---|---|
| 1 | Why was 141 mm strip cut from the 2397 mm side of the OSB boards? | The panel height requires a 2256 mm cut, which is 141 mm shorter than the 2397 mm standard OSB length. |
| 2 | Why is the wall panel height designed at 2256 mm? | Because design customisation is prioritised over standard material size consideration. |
| 3 | Why was the 2397 mm OSB boards sourced? | The 2397 mm OSB is the nearest standard size in the market that delivers the least offcuts. |
| 4 | Why wasn't a custom-size OSB considered to reduce waste? | Because custom-size ordering is expensive and requires more time to source. |

Hence, the root cause of the 141 mm offcuts is the limited consideration of standard OSB sizes and the prioritisation of design customisation. While sourcing custom-size OSB boards could eliminate this waste, the higher cost and longer lead times make it a less feasible option.

**Width-side OSB Boards Offcuts**

These offcuts were produced by the robotic saw when trimming the width-side of the final OSB board to precisely align with the panel edge (see light blue strip in Figure 6). On average, 72 mm-wide offcuts were generated across the eight panels observed at this station. These account for 2% of total OSB use and 6% of total OSB offcuts. To identify the root cause of this waste, the lean 5 Whys technique was applied during interviews, as shown in Table 6:

Table 6: Width-side OSB Offcuts - Root Cause Analysis

| # | Why Questions | Justification |
|---|---|---|
| 1 | Why were limited amount of OSB width-side offcuts generated? | Because only the last OSB board needs to be cut, not every board. |
| 2 | Why was only the final OSB board need to be cut? | Because the timber frame studs are designed in standardised positions that match three OSB sizes of 597, 797, and 1197 mm. |
| 3 | Why were the timber stud positions designed to match OSB sizes? | To streamline the robot operations by limiting the need to cut OSB boards during assembly. |
| 4 | Why is streamlining robot operations prioritised in this case? | Because it simplifies robotic operations, saves time, and limits offcuts to the final board. |

Therefore, the reduction of these offcuts is due to aligning stud positions with standard OSB widths of 597, 797, and 1197 mm. This eliminates the need to cut every board—only the last board requires trimming to match the panel width, while also streamlining the robotic fitting process. Figure 7 shows the robotic saw performing the width-side cut on the final OSB board.

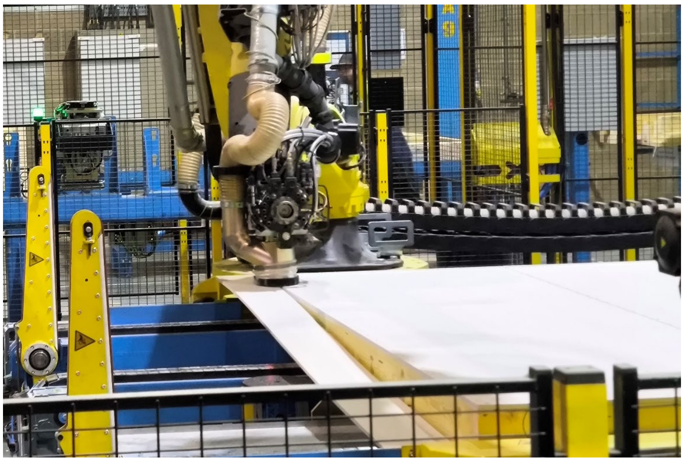

Figure 7: OSB Width-side Offcut Generation

**OSB Opening Offcuts**

These offcuts were generated when the robotic saw cut out sections of the OSB layer covering designated openings (e.g., windows, doors). They account for a significant 19% of total OSB use and 71% of all OSB offcuts. To identify the root cause of this waste, the lean 5 Whys technique was applied during interviews, as detailed in Table 7 below:

Table 7: OSB Opening Offcuts - Root Cause Analysis

| # | Why Questions | Justification |
|---|---|---|
| 1 | Why were OSB offcuts being generated at the openings? | Because full width OSB boards were fitted first, covering the whole panel including the openings. |
| 2 | Why were full width OSB boards being used even over the openings? | To streamline the robot operations in fitting the OSB layer in efficient and timely manners. |
| 3 | Why were the robot operations streamlined by using full boards? | Due to the limited capability of the robotic arms to pick and fit smaller OSB cuts. |

Thus, the root cause is identified as limited capability of the robotic arms to pick and fit smaller filler OSB cuts and the need to keep the robot operations as productive as possible.

# COMPARATIVE ANALYSIS

The results show that the automated station generated about 27% offcuts out of the total OSB use, while the manual station generated nearly 16%. For comparative analysis, each category of offcuts is examined across the two OSB assembly stations, as detailed in the following subsections and summarised in Table 8, which outlines the offcut categories, their associated root causes, and the constraints either sacrificed or promoted.

## LENGTH-SIDE OFFCUTS

The results of this category of offcuts were highly similar. At both stations, the required wall panel height was slightly shorter than the standard OSB board, necessitating a small strip of offcuts to be generated. This resulted in 5.6% and 6% of offcuts out of the total OSB use across the manual and automated stations, respectively. The root cause for these offcuts was identified as design and procurement related. For design, these offcuts could have been avoided if the designers had rounded the panel height to the nearest OSB board length during the design phase. Similarly for procurement, sourcing custom-size OSB boards that meet the required panels height can eliminate the need for cutting and generating offcuts. However, these considerations are not without implications. While changing design can impact the customisation level requested by the customer, ordering an oddly custom size material can result in higher material cost and longer lead times to source.

## WIDTH-SIDE OFFCUTS

The automated station achieved notable savings in width-side offcuts, generating only 2% waste from total OSB use. This efficiency resulted from a cross-departmental arrangement among design, procurement, and production teams, enabling the regular sourcing of two custom OSB widths of 597 mm and 797 mm alongside the standard 1200 mm width. This range allowed designers to round required cuts to fit these three widths. The only exception was the final cut from each board, which produced minimal offcuts (i.e., the 2%) (see the light blue section in Figure 6). In contrast, the manual station produced higher offcut levels, accounting for 6.6% of total OSB use. This is attributed to limited design consideration for standard OSB widths or their multiples (e.g., 33%, 67%). Instead, the design specified highly variable widths, reducing the potential for cutting integration and resulting in greater material waste (see Figure 5).

## FILLER OFFCUTS

These offcuts were generated at the manual station due to the need to perform highly customised cuts (i.e., from the length and width sides of the OSB) to cover the window and door headers' areas (see sections C & F at Figure 4). As a result, notable amount of filler offcuts was generated, contributing to 3.3% of total OSB use. This is attributed to the limited cutting optimisation performed at the whole design package level to keep the production line fed with required OSB cuts on time. However, at the automated station these offcuts were altered by a much worse category of offcuts explained in the next section.

Table 8: Offcuts and Associated Root Causes Categories, and sacrificed/promoted constraints

| Offcuts | Root Causes | Category | Sacrificing | Promoting |
|---|---|---|---|---|
| Length-side Offcuts | Limited standard size consideration | Fragmented Design | Material Efficiency; Productivity | Design Customisation |
| | Limited custom-size sourcing | Off-the-shelf Procurement | Material Efficiency; Productivity | Cost Saving; Time Saving |
| Width-side Offcuts | Limited standard size consideration | Fragmented Design | Material Efficiency; Productivity | - |
| | Limited custom-size sourcing | Off-the-shelf Procurement | Material Efficiency; Productivity | Cost Saving; Time Saving |
| Filler Offcuts | Limited cutting integration | Deficient Production Machinery | Material Efficiency; | Productivity |
| Opening Offcuts | Limited Assembly capability | Deficient Production Machinery | Material Efficiency; | Productivity |

## OPENING OFFCUTS

These offcuts were totally avoided at the manual station since the production process at this factory favours pre-cutting the required OSB pieces before fitting and nailing them. Hence, no OSB layer covered the window/door openings and so no offcuts were generated as a result. In contrast, the automated station favours fitting and nailing the full OSB board sizes and the robots would then cut out excess OSB layer, including that covering the openings. This practice, although avoided an extra step (i.e., OSB pre-cutting before fitting), it caused significant offcuts generation of 19% of the total OSB use.

# DISCUSSIONS

This study investigated how, how much, and why CW is generated in OSC, and whether current lean and technology practices contribute to its reduction. Micro-level analysis of OSB assembly activities revealed that material offcuts were the primary form of CW, with the automated station producing 11% more than the manual one. Root causes, identified using the lean 5 Whys method, were categorised across design, procurement, and production stages.

One key category of the identified root causes is *fragmented design* that overlooks standard material sizes and their multiples. This practice leads to excessive offcuts and unnecessary labour for measuring and cutting. This issue is particularly evident in width-side offcuts at the manual station. Although the station uses an automated segmentation tool to define cuts within each panel (including OSB panels) the tool does not account for standard sizes or their multiples. Instead, it generates highly varied OSB widths that are difficult to integrate without producing significant offcuts. When design customisation is highly rigid, opportunities to minimise offcuts and streamline assembly are limited. This is especially true for length-side offcuts at both stations, driven by strict panel height specifications.

Another key category of root causes is *off-the-shelf procurement*, which relies on sourcing standard market-available sizes without coordination between designers and suppliers to order custom sizes. When design does not align with standard sizes or their multiples, significant offcuts are likely, particularly for length-side offcuts observed at both stations, where neither standard nor custom OSB lengths were considered. In contrast, when a design–procurement arrangement is in place, designers can standardise a limited set of dimensions, and procurement teams can coordinate with suppliers to source them regularly. This approach contributed to the reduction of width-side offcuts at the automated station.

At production level, a key root cause of offcut is the *deficient production machinery*, which contributes significantly to offcut generation. For instance, the robotic arms at the automated station are unable to handle smaller components, such as door and window headers, requiring the use of full OSB boards for these areas and resulting in substantial material offcuts. Although this approach increases offcuts, it simplifies robotic operation and enhances productivity. Similarly, at the manual station, excessive filler offcuts result from the saw's limited ability to optimise cuts efficiently without disrupting the assembly flow. In both cases, equipment constraints compromise material efficiency for the sake of production continuity.

# CONCLUSIONS

This study investigated how, how much, and why CW is generated at the activity level in OSC, and whether current lean practices and technology uptake promote material efficiency. The findings reveal substantial offcut generation of 15.6% at the manual station and 27% at the automated station, primarily due to disintegrated design, limited procurement coordination, and inadequate production machinery. In most cases, material efficiency was compromised in favour of productivity, cost, time, and design customisation. This reflects a limited adoption of lean principles in OSC, particularly Design for Manufacture and Assembly, which is vital for balancing competing project constraints. Technological application was also lacking; for instance, the robotic arm could not handle smaller components, requiring full OSB boards to be placed over openings and later cut out, leading to excessive offcuts. Addressing this issue may involve enhancing robotic capabilities to handle smaller parts or integrating manual support to reduce offcuts without compromising productivity.

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