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Standardization of Prefabricated Wood Panels to Improve Housing Manufacturing in SMEs

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Abstract

Small and medium enterprises (SMEs) are critical actors in housing supply chains; however, they often struggle to adopt industrialized construction. High variability, limited infrastructure, and skill constraints can reduce repeatability and quality. This study shows that SMEs can start with targeted standardization of prefabricated wood panels. A panel library and coded kits support scalable production, repeatable quality, and a structured workflow for light timber framing. Evidence is provided by a Chilean industrial case study using a time-study campaign. The campaign quantified processing, setup, and internal movement times across a five-station manual layout. Results indicate that a standardized panel set for larger housing typologies stabilizes manual operations. Throughput improves only after key bottlenecks are addressed as staffing increases from 12 to 18 operators, enabling production above 200 homes per year. When two of eight activities are automated at Station 2 using CNC (fixing and cutting), annual capacity can approach 300 homes. Overall, the findings suggest a staged pathway for SMEs: standardize first, add selective automation once constraints are removed, and then integrate internal logistics to sustain the transition from craft-based to industrialized housing production.

Keywords: light timber framing; panelized prefabrication; standardization; DfMA; production line balancing

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1. Introduction

The world is under increasing pressure to mitigate climate change. In this context, the construction sector is essential for reducing waste and emissions [1,2]. Timber construction is increasingly being positioned as a sustainable alternative to conventional practices. It can also deliver environmental benefits through carbon storage [3,4]. At the same time, housing programs, especially social and publicly funded schemes, are shaped by demands for rapid delivery, modularity, and predictable quality [5].

Light timber framing responds to these requirements by enabling relatively fast assembly and material efficiency. Therefore, it supports scalable and cost-sensitive solutions aligned with sustainability objectives [6,7]. However, the transition from craft-based production to repeatable off-site fabrication remains difficult. Prefabrication can reduce cost, shorten schedules, and reduce waste on-site. [8,9]. However, SMEs that represent a large share of the construction supply base often struggle to adopt industrialized practices [10].

A primary driver is the limited standardization of components and processes. This limitation undermines repeatability, efficiency, and quality [11]. Infrastructure constraints and limited access to advanced technologies further restrict scaling. They also delay the transition to more industrialized operating models [12,13]. Skills gaps intensify these barriers. Without sufficient training in software-assisted manufacturing, process planning, or semi-automated layouts, firms may lose competitiveness. This challenge is often more acute in emerging economies, where financial, technical, and cultural barriers are typically stronger [14,15]. Recent research reports progress in prefabrication of wood. Platform-oriented approaches and fabrication–assembly workflows have been proposed to improve re-usability across projects [16,17]. Design for Manufacture and Assembly (DfMA) and connector-focused design have supported early families of standardized components for timber manufacturing [18,19]. Within DfMA, standardization is a core principle because it reduces the variety of components and the diversity of the material. This, in turn, reduces complexity, cost, and assembly time. In parallel, Modern Methods of Construction (MMC) provide a structured lens to classify industrialization levels. These levels range from components to volumetric modules and connect material systems with performance objectives [20,21]. In practice, MMC initiatives have helped formalize processes and products. They do so by decomposing the delivery into 1D, 2D, and 3D elements and by improving system integration [22,23]. Complementarily, DfMA frames industrialization as an end-to-end philosophy, from prefabrication through assembly. It has a documented potential to reduce time and costs while improving the final quality [24].

The Wood Industry 4.0 agenda also enables connectivity, automation, data analytics, and machine learning. These capabilities can be used to monitor production systems and support iterative improvement through digital platforms [25,26]. Manufacturing-oriented modeling is also being applied to timber construction. Examples include the simulation of workstations and component–platform configurations [27,28]. However, persistent gaps remain for SMEs. These include insufficient infrastructure for reconfigurable or semi-automated handling, limited access to simulation and optimization tools, and a shortage of standardized component libraries adaptable to regional needs [29,30].

This study aims to demonstrate that SMEs can start with the targeted standardization of prefabricated wood panels. The approach uses a panel library and coded kits to enable scalable production, repeatable quality, and a structured workflow for light timber framing. This strategy innovates through standardization aligned with DfMA as an operating philosophy and can serve as a reference for SMEs in emerging markets, from Chile to Latin America.

To implement the proposal, we defined a manufacturing design and a work sequence for panel production. We then conducted a time-study experiment to quantify processing times by activity and workstation. Next, we implemented a discrete-event simulation of the entire production system [31]. This simulation evaluates how component standardization affects aggregate output and how selective automation of key tasks may further increase throughput. The broader contribution is practical. It translates advanced manufacturing and design approaches into an implementable pathway for resource-constrained companies. It also supports a wider adoption of timber construction while reducing on-site material waste.

1.1. From Fragmentation to Integration: A Pathway to Platform Adoption

Contemporary construction delivery is often organized around one-time projects. This creates horizontal, vertical, and longitudinal fragmentation. The result is technically and financially inefficient [32,33]. Horizontal fragmentation arises from the separation of specialized disciplines (e.g., electrical, thermal, plumbing, and fire resistance) between

procurement packages. Vertical fragmentation occurs in all stages of the life cycle (design, construction, and operations). Each phase typically involves different stakeholders and incentives. Longitudinal fragmentation arises from project-to-project discontinuity. Teams rotate by assignment rather than specialization, and learning effects are lost when firms cannot repeatedly collaborate on similar products [32].

Evidence linking fragmentation with weak productivity performance has strengthened the case for platform-oriented industrialization. For example, Kauppinen et al. [34] report that productivity gains are associated with greater off-site prefabrication and with platform logics that enable reuse and repeatability across projects. Similarly, Hall et al. [32] describe a shift from "fragmentation to integration" through business models that prioritize product platforms, outlining three archetypes:

(a) Collaborative platforms enabled by satellite factories achieve partial integration (vertical, horizontal, and longitudinal).
(b) Digitally integrated systems without owned factories, where cloud-based design and configuration enable distributed manufacturing through peripheral suppliers, emphasize horizontal and longitudinal integration.
(c) Hierarchical firms that integrate product architecture, processes, and owned manufacturing plants require high investment and enable deeper integration across dimensions.

A platform strategy intended for broad uptake should remain feasible across firm sizes, workforce specialization, and process–simulation capability. These factors should be treated as explicit design constraints rather than as implicit assumptions.

1.2. Industrialization as Part of the Solution

Industrialization in timber construction has been demonstrated through various strategies. Illustrative cases include Tallwood House (Brock Commons), a hybrid high-rise that combines a concrete core with mass-timber elements [35]. Other examples include cross-laminated timber delivery models such as those reported for Xlam Dolomiti [36]. Vertically integrated initiatives such as Katerra also aimed to connect the value chain from forestry to the end user [35]. While these examples differ in scale and governance, they underscore the value of repeatable product definitions, coordinated supply chains, and manufacturing-led thinking in housing delivery.

The United Kingdom provides a prominent policy-and-research setting for platform-based construction. It is supported by science–industry programs associated with Innovate UK and the Industrial Strategy. In this ecosystem, the Transforming Construction Network Plus advances themes connecting industrialization, business models, and platform thinking. These themes include changing business models [35], platform thinking for construction [37], supply-chain productivity and information flows [38], and the role of industry–university collaboration in sector transformation [39]. Internationally, a high penetration of industrialized approaches has been observed in North America, spanning prefabrication, pre-assembly, modular, and volumetric construction [40]. Product-platform perspectives have also been documented in Sweden, emphasizing standardized and reusable digital information for material tracking and industrialized delivery [38]. In New Zealand, prefabricated housebuilding has been analyzed through supply-chain structure and the role of local producers [41].

In Latin America, Chile leads in timber construction. Wooden houses reach 19% of the total housing stock, and this share is increasing due to sustainability and productivity drivers [42,43]. Construction techniques include prefabricated panels and industrialized approaches. A group of firms has invested in technology and workforce development, together reaching an annual supply of 20,000 industrialized homes. Prices for social housing (50–60 m^2) range from 50,000 to 70,000 USD, depending on finishes and standards [44,45].

However, automation in the modular timber housing sector remains at an early stage. Most SME processes are still manual, with 10 to 50 employees focused on residential or small-scale projects. This limits productivity and scalability, with typical output between 10 and 80 housing units per year. Many firms also face difficulties integrating more automated processes due to investment constraints [46,47].

Overall, the literature supports platform standardization based by selective automation and digital methods as a credible pathway to improve productivity and quality in construction. However, emerging markets face persistent constraints in investment capacity and human-capital readiness. These constraints slow adoption and limit the translation of industrialization concepts into practice. This motivates applied studies that start from manual production realities. It also motivates quantifying productivity gains achievable through standardization, logistics, and targeted technology deployment.

2. Materials and Methods

2.1. Case Study Context and Standardized Platform

The study was conducted at Rima's facility (www.gruporima.cl (accessed on 15 February 2025), a Chilean company specialized in timber-based manufacturing systems that supply housing production panels. Rima manages their own family of components on a standardized platform. This platform supports multi-panel design within a manufacturing process (patent under processing since 2024), formalizes dimensional rules, tolerances, and coding conventions intended to (i) reduce non-value-adding time, (ii) minimize material waste, and (iii) improve repeatability across projects. In addition, the use of explicit tolerances in design and cutting aims to reduce assembly errors and material overconsumption, thus improving the technical and economic feasibility of SME-scale deployment.

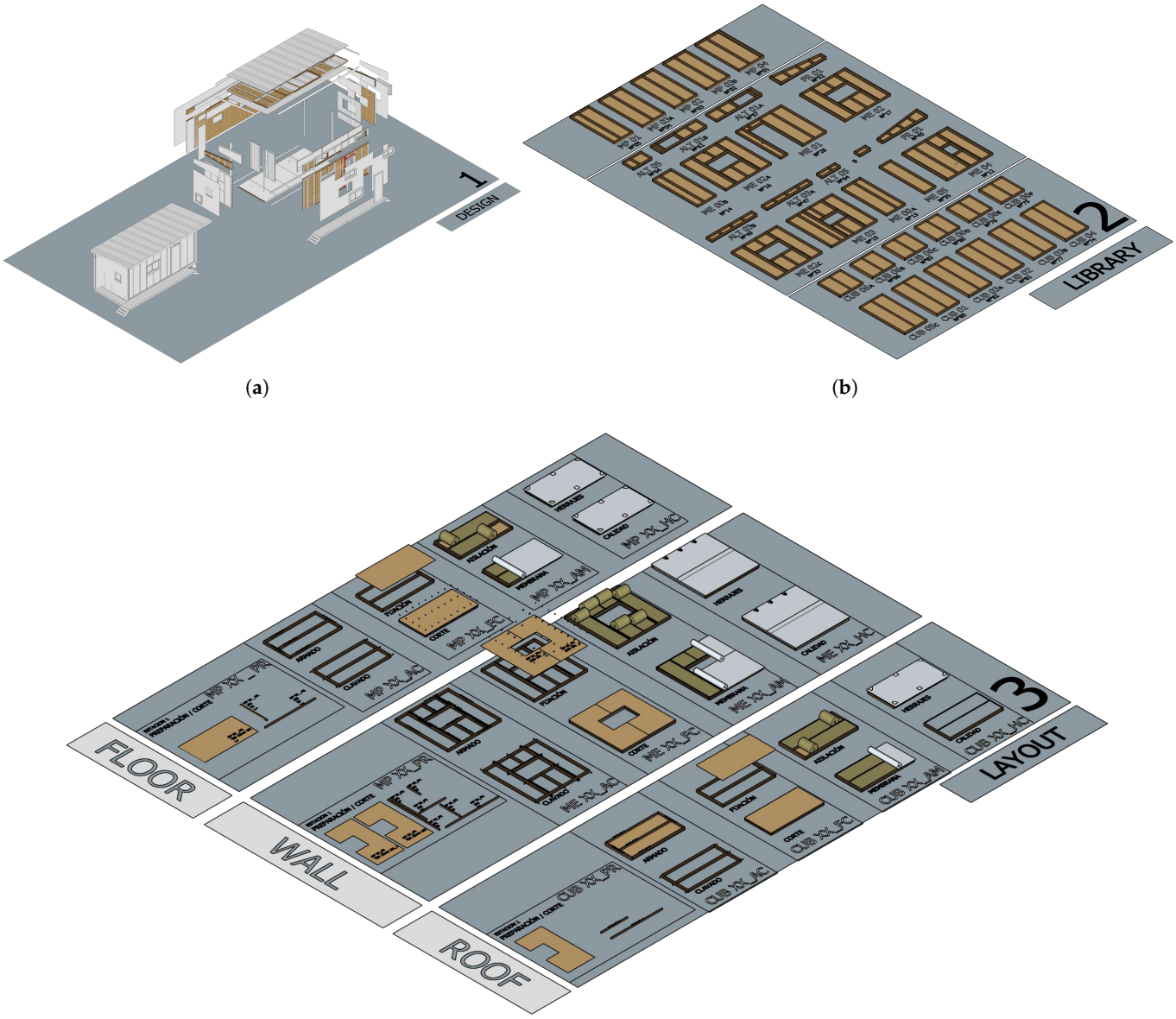
Support for modeling and simulation was provided by the Centro Avanzado de Simulación de Procesos (CASP) (www.casp.ubiobio.cl (accessed on 15 February 2025)), Universidad del Bíobío, Chile. The empirical work focused on the prefabrication of a 14 m^2 base housing module, denoted as *1X*, which is decomposed into a standardized set of prefabricated components: eight wall panels, five floor panels, five roof panels, six mezzanine panels, and two gable panels. This module was designed to scale up to *8X* units using a light timber frame system.

2.2. Platform: Design, Library, and Layout

The experimental procedure followed the operational workflow currently used by Rima in its manufacturing line, which uses three phases:

1. Design: translation of standardized components into cutting plans (detailed instructions for material cutting), material bills (comprehensive lists of needed materials) and assembly logic, aligned with the DfMA principles (Figure 1a).
2. Library: organization of parts and sub-parts into panel-specific kits (Figure 1b), enabling structured execution with reduced rework.
3. Layout: execution of manual prefabrication in a five-station layout, with incremental opportunities for partial automation (Figure 1c).

In the Library phase, typical parts included studs, beams, structural boards, insulation, fasteners, membranes, and connectors. The kits were prepared according to each type of panel and included detailed material lists, technical drawings, and an assembly sequence. This coding supported traceability throughout each fabrication stage (Figure 1).



(**a**) (**b**)

(**c**)

Figure 1. Design-to-library workflow used in the *1X* manufacturing experiment: (**a**) standardized panel definition and component breakdown; (**b**) panel kit structure (materials, drawings, and assembly sequence); (**c**) manufacturing matrix enabling multi-panel planning and repeatable execution. Source: Rima.

2.3. Manual Layout and Stations

Standardized components were prefabricated through five stations (indexed 0–4), implemented consistently throughout the experiment:

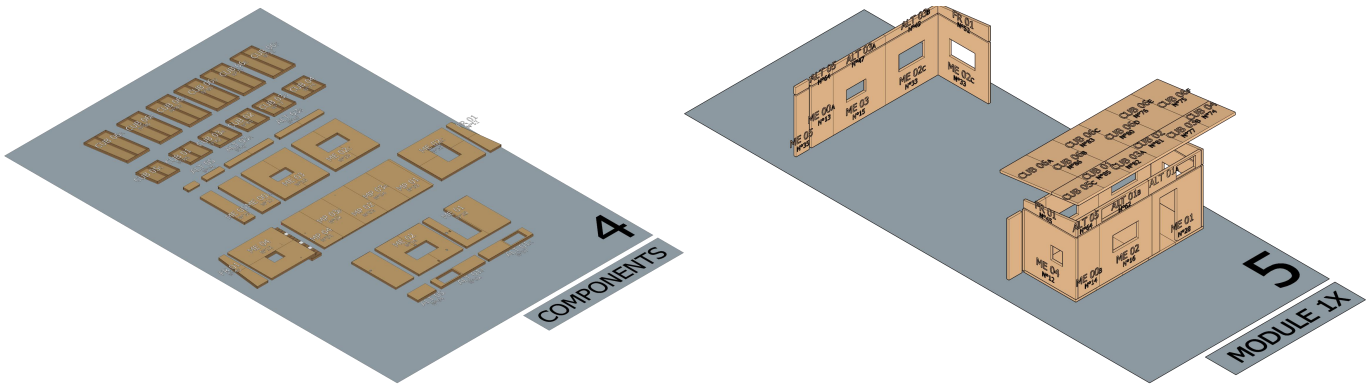
- Station 0—preparation: Cut graded structural timber and structural boards, then bundle into coded packages for transport to the framing station.
- Station 1—assembly/nailing: Timber and boards are positioned on a manufacturing table according to the assembly drawings. Framing and pneumatic nailing are performed. The coded panel is then transferred to the fixing and cutting station.
- Station 2—fixing/cutting: Panel bracing involves two activities: board cutting and pneumatic fastening of the structural panel to the frame panel. The code is updated and the panel is then transferred to the panelization station.

- Station 3—insulation/membrane: Insulation is installed manually in the panel. The weather-resistive membrane is mechanically fastened. The panel code is updated and then transferred to the output station.
- Station 4—connector/sealing: Connectors and hardware are installed. The membrane junctions are sealed to ensure correct integration during final assembly on-site.

The stations were designed to group consecutive activities to improve flow and reduce handling overhead. The baseline process was manual. The layout was intentionally defined to allow progressive and partial automation in accordance with SMEs' constraints. The observed station- and activity-level times were later used as empirical input for the evaluation plan based on the scenario (Section 2.8).

2.4. Additional Platform Phases: Components and Module Aggregation

To extend the analysis from individual panels to scalable housing configurations, two additional phases were defined. These are **Components (4)** and **Module (5)**, summarized in Figure 2. The *1X* module was selected as the reference unit because it meets the above manufacturing constraints and remains scalable for family variants.



(**a**) (**b**)

Figure 2. Component-to-module aggregation scheme used to scale the *1X* base unit into larger housing typologies: (**a**) standardized component families and equivalence rules; (**b**) module composition and scalability logic. Source: Rima.

2.5. Real-Time Measurement Campaign

A time study was conducted during the prefabrication experiment. Data were collected for each station and activity across all manufactured components. The measurements documented the following:

1. Processing time (value-adding operation time);
2. Material movement time (work-in-process transfers between stations);
3. Setup time (preparations and adjustments);
4. Intermediate auxiliary time (tasks that keep resources occupied without directly transforming the product).

Figure 3 illustrates the task allocation structure used to standardize measurements between the stations and their activities, showing a sequence of tasks for the activity/station. For example, Station 1 includes the following:

Processing time: Execution of panel assembly/structural nailing execution;

Material movement time: Panel transition 1a–1b/panel transfer to Station 2;

Setup time: Setup 1a—inspection checklist for matrix layout/setup 1b—visual inspection of stud-to-plate connection;

Intermediate auxiliary time: Quality control (visual inspection)—1b. Data were collected by station/activity (1a–1b, 2a–2b, 3a–3b, 4a–4b) and separated by panel type: wall (ME00–ME04), roof (CUB01–CUB03, ALT01–ALT06, FRO01-FRO02), and floor (PIS01–PIS03). For production time availability and material cost restrictions, it was possible to obtain five observations per panel, sampled for each activity and station, as shown in Table 1. Given this small sample, special care was taken to use the appropriate statistical analysis (maximum likelihood analysis and graphical approach), reinforced with expert judgment [31].

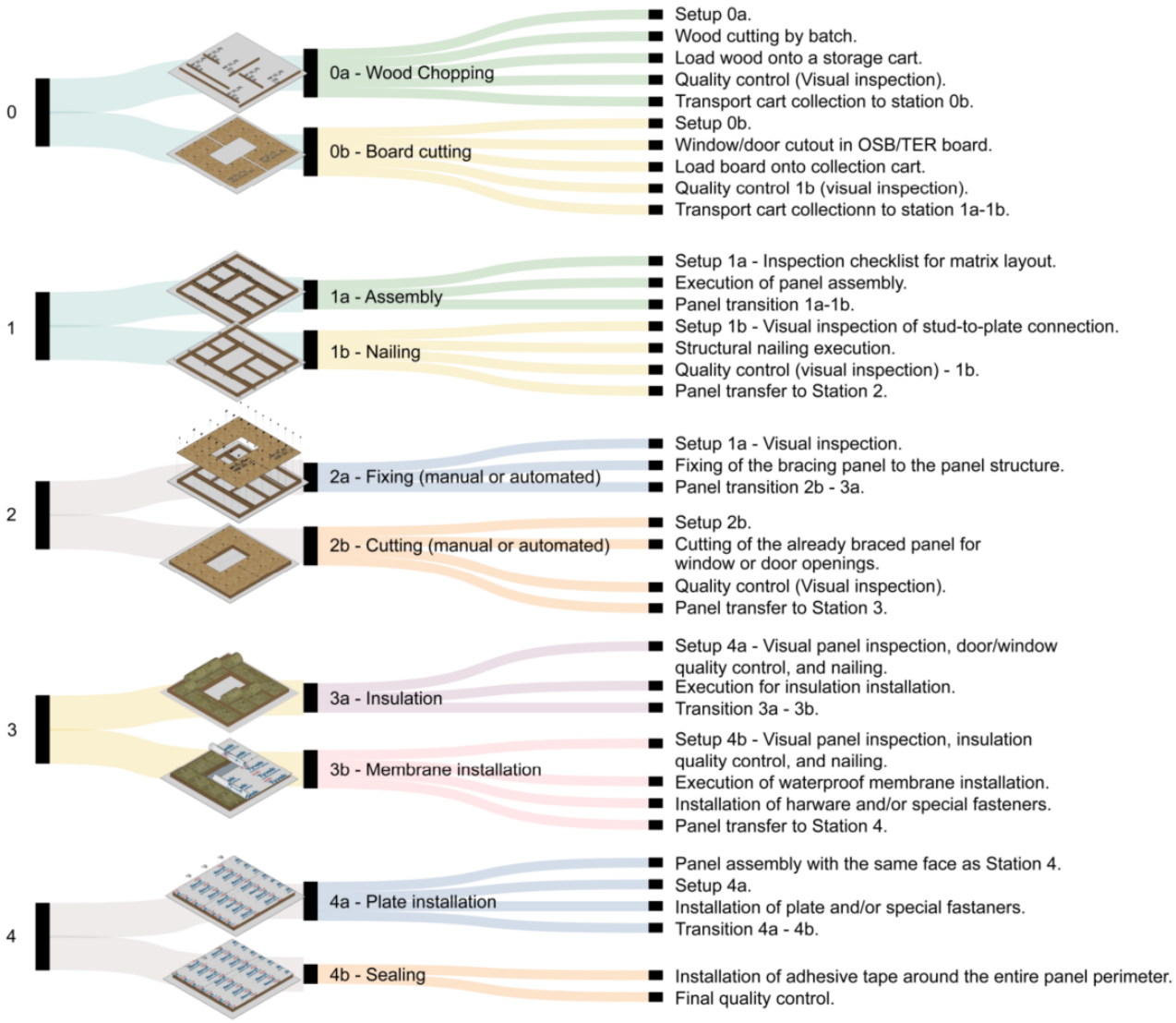


Figure 3. Task allocation framework by activity and station used for the time study. Source: authors.

To analyze the data collected, a discrete-event simulation was selected. Simulation stands out in wood-housing manufacturing modeling and analysis because it captures something and traditional analytical tools simply cannot: stochastic variables, a resource constraint reality that works with a natural material and complex flow of tasks.

The dataset served three purposes: It was used to parameterize the discrete-event simulation model. It helped evaluate the scalability of the *1X* unit into multi-module housing variants. It also provided a baseline for continuous improvement iterations. The panel/component/module library for the scalable family *1X–8X* was used as the reference configuration.

Table 1. Definition of line configuration, station tasks, and assigned operators.

Line Component	**Station 0**	**Station 1**		**Station 2**		**Station 3**		**Station 4**	
Code	Wood Chopping	Assembly (A) Nailing (N)		Fixing (F) Cutting (C)		Insulation (I) Membrane (M)		Plate (P) Sealing (S)	
L1—Wall		A	N	F	C	I	M	P	S
	m	m	m	m a	m a	m	m	m	m
ME00–ME04	5	5	5	5 5	5 5	5	5	5	5
L2 – Roof		A	N	F	C	I	M	P	S
	m	m	m	m a	m a	m	m	m	m
CUB01–CUB03	5	5	5	5 5	– –	5	5	5	5
ALT01–ALT06	5	5	5	5 5	– –	5	5	5	5
FRO01–FRO06	5	5	5	5 5	– –	5	5	5	5
L3 – Floor		A	N	F	C	I	M	P	S
	m	m	m	m a	m a	m	m	m	m
PIS01–PIS03	5	5	5	5 5	– –	5	5	5	5
ALT02–ALT05	5	5	5	5 5	– –	5	5	5	5

2.6. Simulation Design and Demand Specification

The simulation follows the logic of the platform, which has three steps:

1. Selection of representative wall, roof, and floor panels from the *1X* module;
2. Construction of housing variants by increasing the number of *1X* units to define *2X*, *3X*, and *4X* configurations;
3. Addition of *1X* modules to represent larger variants (*4X*, *6X*, *8X*) within the same family.

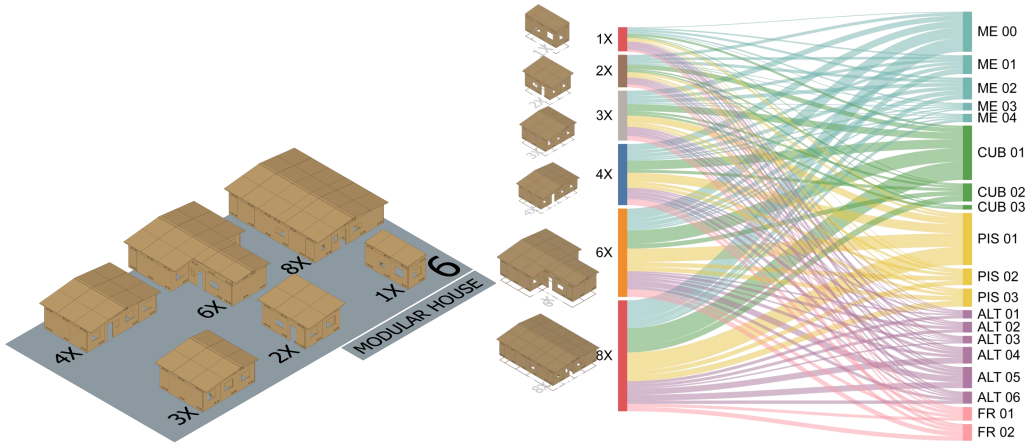
All typologies (*1X*, *2X*, *3X*, *4X*, *6X*, *8X*) were mapped into an equivalent panel format, ensuring a manufacturing configuration in the layout. The resulting workload specification enabled plant-level estimates for different operating scales.

The production program included 19 component types (ME00, ME01, ME02, ME03, ME04, CUB01, CUB02, CUB03, ALT01, ALT02, ALT03, ALT04, ALT05, ALT06, FR01, FR02) to build the six housing typologies, summarized in Figure 4. A representative prefabrication mix was defined at 50 % for the *4X* typology (about 52 m^2), serving as a proxy for an average social-housing unit. Components were assigned to each prefabrication line, covering walls, roofs, and floors. This setup supported either inventory buffering or direct dispatch to the site for mechanized assembly. More than 200 unit combinations were sampled by replicating a typical panel manufactured according to manual–man–machine station logic (Stations 1–4).

After data tabulation, activity times were fitted using a Weibull distribution. This approach was chosen for its flexibility in representing the asymmetric variability seen in industrial operating activities [31].

2.7. Manual vs. Automated Experiment for Fixing and Cutting Operations (Station 2)

To quantify the potential productivity gains from targeted automation, a focused experiment was conducted at Station 2, using a three-axis CNC machine from company FacilCNC, Villa Alemana, Chile The technical details of the CNC automation process consist of fixing with a manual pneumatic nailer versus an automatic pneumatic nailer, mounting on a CNC machine head, and cutting with a manual router versus a router on a computer numerical control (CNC) machine. In practice, to perform a dual function—fixing and cutting— the CNC was adapted with an electronic controller, motors, and fastening elements so that it could move along the x and y axes, differentiating the z axis to regulate operating height by changing the switch and management software for the fixing and cutting route.



(**a**) (**b**)

Figure 4. Component families and housing typology scaling used to configure the simulation workload: (**a**) typology growth logic from *1X* to *8X*; (**b**) component set and equivalence structure. Source: authors based on Rima's definitions.

Automated process times were measured for the two activities considered most feasible for substituting manual labor with technology: board cutting and board fixing. Each automated activity was observed 20 times (five replications by panel-ME01, ME02, ME03, ME04), including operator actions required for mechanized loading, setup validation, and CNC software operation.

Once the sampling data between manual and CNC activity had been obtained, a statistical evaluation was performed for the validation of data samples using the Kruskal–Wallis test (K-W test) [31]. This test checks whether two samples are homogeneous (come from the same population). Calculate a statistical test and compare it with the critical value for a certain degree of significance (alpha). If the calculated statistic is greater, the null hypothesis is rejected (homogeneity is rejected). The K-W test showed statistically significant differences between groups r1–r5 and r6–r10 (H = 26.444, gl = 1, $p < 0.001$), indicating that both datasets do not come from the same population.

2.8. Plant Scaling and Production-Line Configuration

Plant-scale projections were obtained through simulation (www.flexsim.com). The modeled plant included three specialized manufacturing lines:

- L1: walls;
- L2: roofs (including mezzanine and gable-related components);
- L3: floors (including selected mezzanine components).

The baseline model used manual–man–machine logic across the entire layout. Automation was introduced only at Station 2, generating three scenarios:

1. Manual/Manual: fixing and cutting performed manually;
2. Manual/Automated: one of the two automated activities (fixing/cutting);
3. Automated/Automated: both activities automated via CNC.

Component assignments followed a specialization and line-balancing rationale. For example, L1 processed wall components (ME00–ME04), L2 processed roof/mezzanine (CUB01–CUB03, ALT01, ALT06, FRO01–FRO02), and L3 processed floor and remaining mezzanine components (PIS01–PIS03, ALT02–ALT05). Logistics considerations (internal flows and handling) were incorporated to keep variability within operationally realistic ranges and to mitigate internal transport as a bottleneck. Figure 5 summarizes the allocation of components by housing typology and manufacturing line. For example, in the

4X typology, it comprises 81 panels, distributed into 26 (L1), 26 (L2), and 29 (L3), which, in turn, are broken down into the coded panels shown in the image.

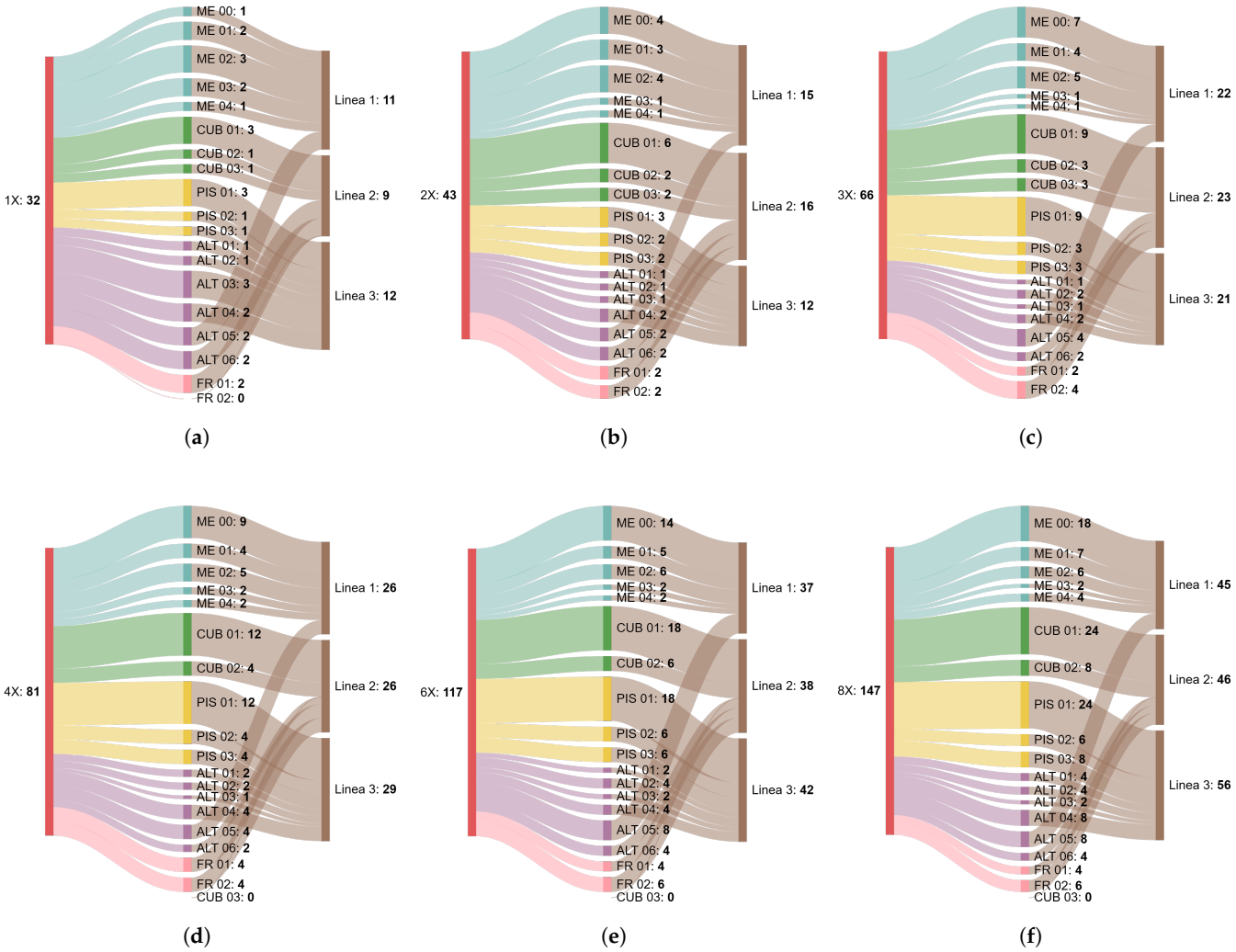


Figure 5. Allocation of components to manufacturing lines (L1–L3) for scalable housing typologies (**a**–**f**) *1X*, *2X*, *3X*, *4X*, *6X*, and *8X*. Source: authors and CASP UBB.

2.9. Effective Operating Factor and Labor Balance

For simulation purposes in this study, it was proposed to apply 80 % of the total available productive time, which results from deducting downtime, setup, configurations, minor incidents, maintenance, and unforeseen events from the total available time (20 days per month at 7.5 h per day). This adjustment was used to produce conservative and relevant scaling estimates for the plant.

To determine the number of replications to run the simulation for a productive time of 80 %, the following conditions were fixed: maximum error (ME) of 10 % of the sample mean (Mean), 20 initial replications, and the confidence level of 95 % for the resulting confidence interval (CI). The number of replications will be appropriate if half the obtained CI is less than or equal to the ME. With reference to Table 2, the observed half-width confidence interval (CI) of 4.0 is substantially smaller than the maximum error (ME) of 29.7. We conclude that 20 replications are sufficient for the purposes of this experiment.

A sensitivity analysis was conducted for the operational plant factor (70 %, 80 % and 90 %), with the resulting values shown in Table 2. The CI for a 95 % confidence for each operating factor was [256.6, 263.8], [292.8, 300.9], and [330.0, 338.5], respectively. It can be

seen that the intervals do not intersect, the operating factor affects the number of houses produced, and the Standard Deviation is very small compared to the corresponding Mean.

Table 2. Statistical results with 95% confidence interval.

Scenario	95% Confidence Interval		Mean	STD	Half CI	ME
	Lower	Upper				
90% Availability	330.0	338.5	334.3	9.1	4.3	33.4
80% Availability	292.8	300.9	296.9	8.6	4.0	29.7
70% Availability	256.6	263.8	260.2	7.8	3.6	26.0

The labor balancing was proposed on three simulation scenarios: (Manual/Manual) was defined with an initial staffing plan distributed across the three production lines and four value addition stations (Stations 1–4), while (Manual/Automatic and Automatic/Automatic) were evaluated for Station 2, enabling combined sensitivity analysis depending on automation level.

The following conditions were considered to assign a labor charge:

- Station consolidation: consecutive activities are grouped within stations to improve resource utilization and flow.
- Operators per station: 1–2 operators are assigned per station, depending on the automation level and workload.
- Floating support team: 2 operators are assigned to internal logistics (movement of parts and kits across stations and lines) to prevent transport-related congestion.
- Staffing levels: three staffing alternatives: 4 operators/line (12 total), 5 operators/line (15 total), and 6 operators/line (18 total).

3. Results

Using a standardized component platform implemented through a panel library and repeatable manufacturing rules enabled four practical advances: (i) isolating and controlling a meaningful portion of production variability, (ii) quantifying the impact of substituting labor with technology in two of the eight activities, (iii) estimating the throughput response to additional staffing, and (iv) identifying where automation becomes necessary rather than optional. We validated a baseline for an SME-oriented, predominantly manual manufacturing layout. This layout is organized into three production lines (L1: yellow, L2: green, L3: orange), four stations, and eight core activities. Figure 6 summarizes the primary outcome of the study. The simulation outputs included annual production volume and station utilization profiles.

In addition, they reflected the bottleneck shifts after reallocating labor, such as introducing a second operator at one or more stations. All outputs were generated under an upper bound of 18 operators for the entire manufacturing system. Three prefabrication policies were evaluated:

- Manual/Manual (MM).
- Manual/Automated (MA).
- Automated/Automated (AA).

where MA and AA refer to the automation of Station 2 activities. Table 3 lists the simulated scenarios. These combine staff levels (12, 15, and 18 operators) with the location of the additional operator(s) within each policy.

Figure 6. Simulated plant layout for production lines L1–L3 under the 18-operator configuration (6 per line). Source: authors.

Table 3. Definition of staffing and service-policy scenarios across stations.

Scenario	Operators per Line (Total)	Stations with 2 Operators	Stations #1, #3, #4	Station #2
MM_12	$4+4+4=12$	–	M/M	M/M
MM_15	$5+5+5=15$	1	M/M	M/M
MM_18a	$6+6+6=18$	1 and 2	M/M	M/M
MM_18b	$6+6+6=18$	1 and 3	M/M	M/M
MA_12	$4+4+4=12$	–	M/M	M/A
MA_15	$5+5+5=15$	1	M/M	M/A
MA_18a	$6+6+6=18$	1 and 2	M/M	M/A
MA_18b	$6+6+6=18$	1 and 3	M/M	M/A
AA_12	$4+4+4=12$	–	M/M	A/A
AA_15	$5+5+5=15$	1	M/M	A/A
AA_18a	$6+6+6=18$	1 and 2	M/M	A/A
AA_18b	$6+6+6=18$	1 and 3	M/M	A/A

3.1. Combined Effect of Standardization, Automation, and Line Integration

The simulation results are interpreted through three operational drivers that position an SME for scaling: Automate, Standardize, and Integrate. Here, Automate means include technology grade, Standardize means moved to a platform logic, and Integrate means "chain" processes across lines and stations. Figure 7 conceptualizes the transition from a one-time project-based manufacturing to repeatable product/platform logic. The three prefabrication policies (MM, MA, AA) are represented as balls 1–3 (fuchsia color). They show how throughput usually improves as these drivers are progressively adopted. In particular, the results indicate that an SME can increase the manufacturing scale from a manual baseline without assuming that technology is the only viable path.

Figure 7 shows the direct relationship between the main axes: Technology expresses the level of process automation, and Platform expresses the level of industry standardization, measured as the evolution between fragmentation and integration of industrialized construction projects.

In the traditional prefabricated housing industry, these two axes have a direct relationship with the size of the company due to access to investment, human capital, and knowledge, when operating in markets where industrialization is well established. These companies are identified with the green and blue balls that are positioned on the graph according to how they serve their customers—by project or by product platform—giving rise to the third axis (diagonal) that depends not only on size but also on their strategic decision to standardize their products and operations.

This is the paradigm expressed in this study: an SME (orange ball) can decide to operate in a fragmented or integrated industry. The results of the simulation open up a new reality, where it is proven that it is possible to standardize processes and products with adequate investment in technology that replaces labor, in balance with the scaling of their business.

This is the path followed by balls 1–3 (fuchsia color), which represent the response to selective automation, achieving a production of close to 300 homes per year. Therefore, the decision to scale up to 500 or 750 homes will depend not only on technology but also on the maturity of the platform that the SME intends to promote.

From this perspective, an opportunity arises for the prefabrication of homes in emerging markets on their path to industrialization.

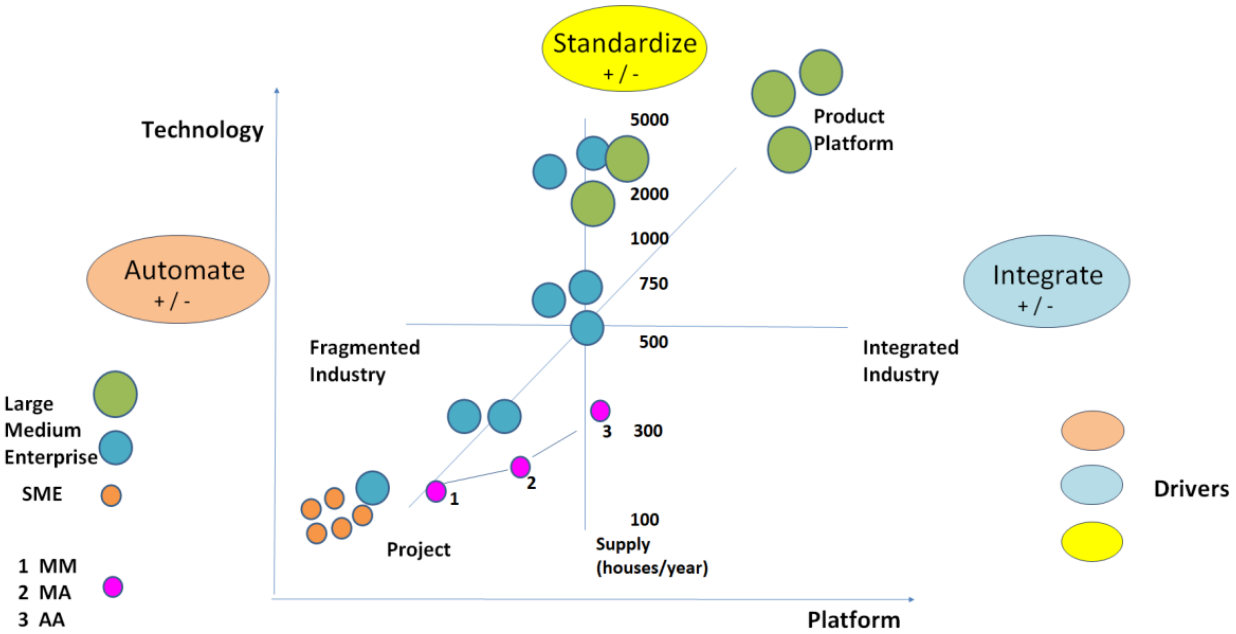


Figure 7. Strategic map illustrating the combined effect of standardization, automation, and process integration across three operating policies. Source: authors.

3.1.1. Standardizing Production

The deployment of a component platform based on DfMA methodology changes the operating logic from "build-to-project" to a standardized production. This focus allows panel types for a scalable housing mix. The platform allows pre-definition of equivalent panels, repeatable kits, and consistent station workloads. These features support continuity in manual operations. In the baseline configuration, 12 operators were assigned in three lines (4 per line, 1 per station), providing a stable reference for annual production planning.

3.1.2. Substituting Labor with Technology at Station 2

Automation was evaluated for two activities within Station 2: fixing and cutting. When staffing was kept constant at 12 operators, annual output remained essentially unchanged at 179 houses/year in MM, MA, and AA. These results occurred because the bottleneck was not Station 2, but Station 1 on the wall production line (framing/nailing). The upstream constraint limited the release of the panel and suppressed the benefits of faster downstream operations. Under these conditions, adding technology yielded negligible returns. The system was required to fix the bottleneck through reallocation of staff.

3.1.3. Effect of Additional Staffing and Interaction with Automation

Figure 8 summarizes the joint effect of adding staff and automation at Station 2, from 12 to 18 operators (+33%), on annual output:

- 15.7% for MM_18b (213 houses/year);
- 29.1% for MA_18b (254 houses/year);
- 39.4% for AA_18b (297 houses/year).

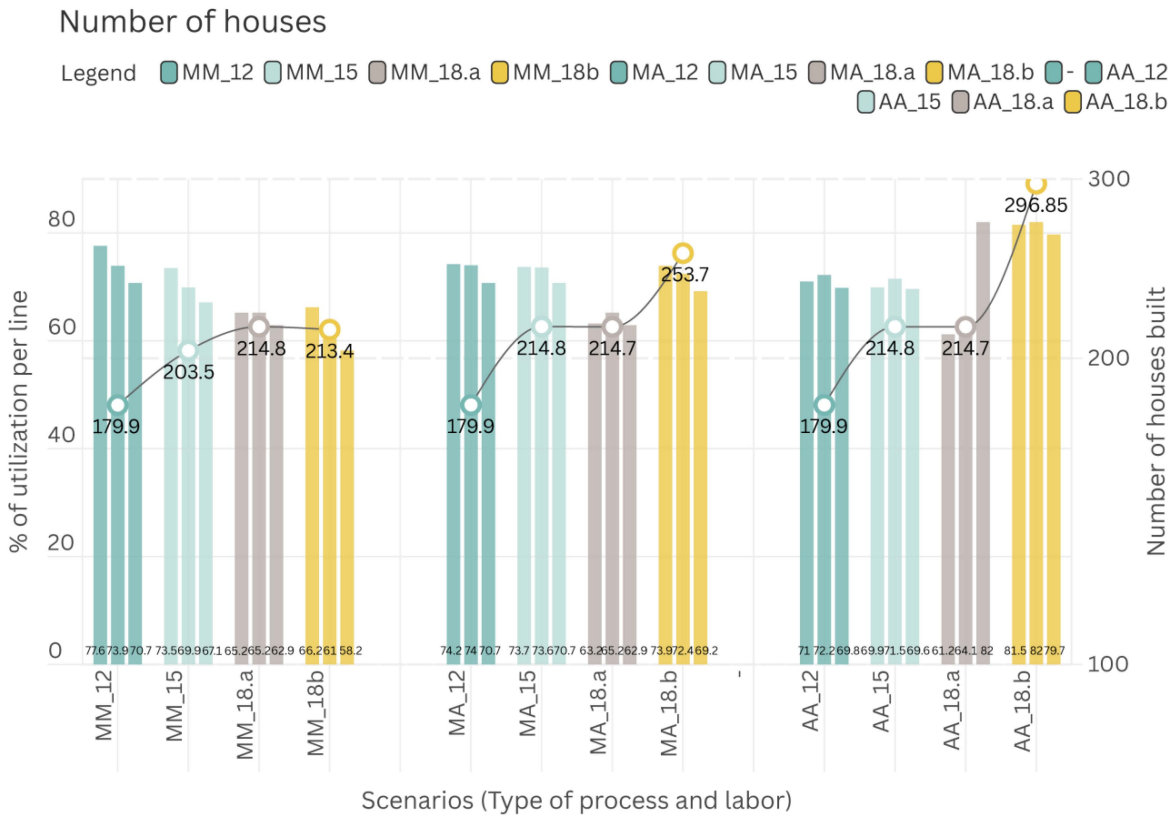


Figure 8. Annual production response to staffing level and Station 2 automation policy. Source: authors.

These figures are compared to the baseline of 12 operators (MM_12, MA_12, AA_12).

When comparing policies at the same 18-operator staffing level, the marginal automation gains were more moderate. MA increased output by 15.9% over MM. AA increased output by another 14.6% over MA. Thus, automation effects are meaningful but depend on the removal of upstream bottlenecks. On average, the observed ∼15% gain from automation under managing bottlenecks conditions supports exploring technology insertion at the intra-activity level, as well as process engineering for internal logistics (transport, lifting and buffering).

3.2. Station Utilization and Bottleneck Migration Across Scenarios

The labor force has a direct effect on production, creating a balance between workloads and bottlenecks.

Figures 9–11 show how workloads and bottlenecks (red color) changed at each station and across production lines (L1–L3) as teams revised staffing and automation plans.

With MM_12, no additional labor was assigned and production was limited to approximately 180 houses/year because Station 1 (framing/nailing) could not increase panel output with a single operator. Under MM_15, one operator per line was added (at Station 1). The bottleneck then moved to Station 2, increasing annual production to 203 houses/year (MM), 215 houses/year (MA), and 215 houses/year (AA). For the 18-operator case, two staffing placements were tested:

- MM/MA/AA_18a (two operators at Stations 1 and 2): the bottleneck moved to Station 3, and production stabilized near 214 houses/year in all policies, indicating that Station 3 became limiting once upstream capacity increased.
- MM/MA/AA_18b (two operators at Stations 1 and 3): the bottleneck returned to Station 2. The Automation at Station 2 then produced clear throughput gains. Production reached 213 houses/year (MM), 254 houses/year (MA), and 296 houses/year (AA).

These results emphasize that automation returns are highly sensitive to labor placement and station limitations. Targeted automation is most valuable when it addresses the active bottleneck or anticipates where one will occur. Improving a non-limiting step has less impact.

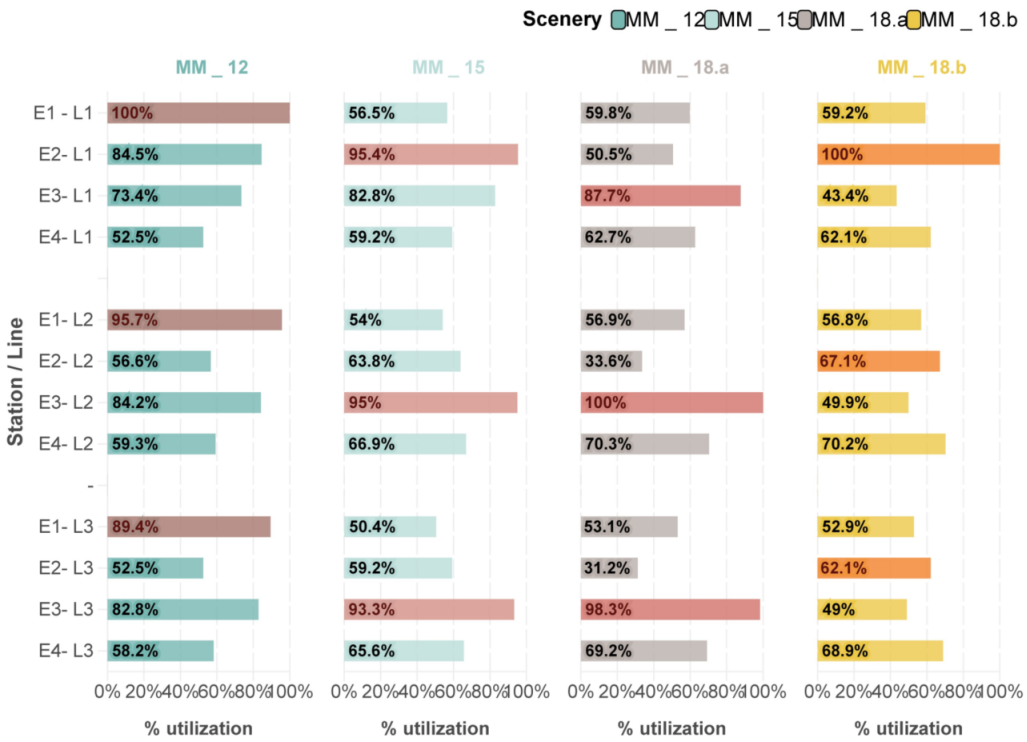


Figure 9. Line-level utilization and throughput response across prefabrication scenarios. Source: CASP and authors.

There is clearly a direct relationship between empirically outcomes (throughput, bottleneck behavior, workflow stability), and the expected benefits (e.g., production, scalability) are now framed as SME transfer case futures.This relation strengthens the linkage between the staged pathway (manual, semi-automated, selectively automated) and the simulation outcomes presented.

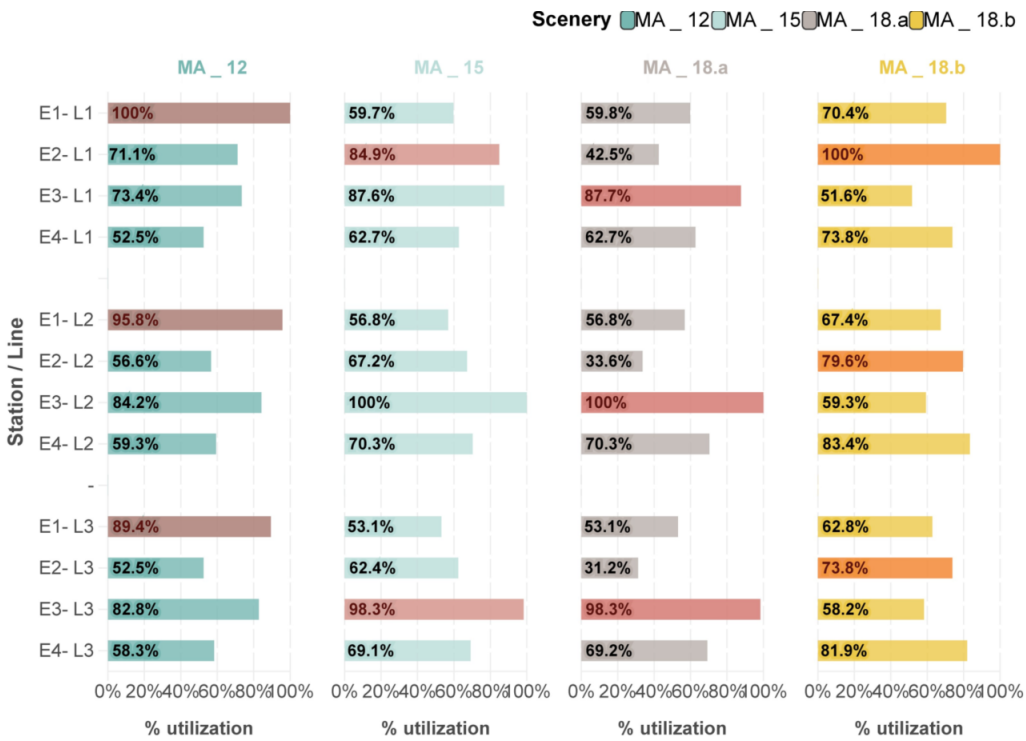


Figure 10. Station utilization profiles by line (L1–L3) for the staffing and automation scenarios. Source: CASP and authors.

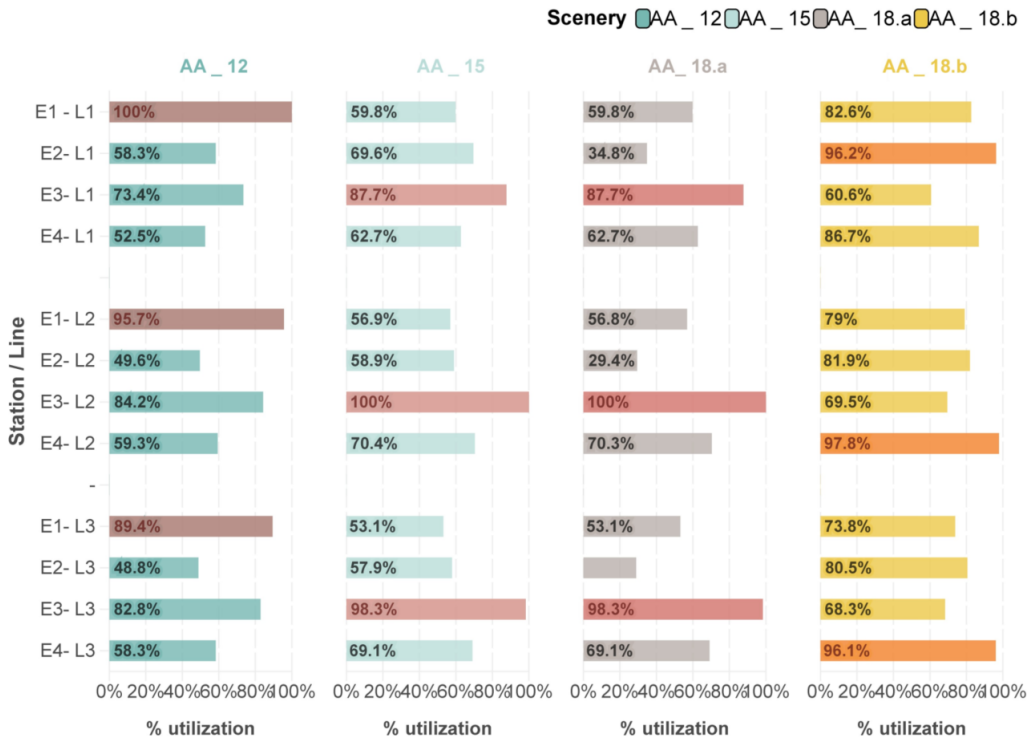


Figure 11. Bottleneck migration across stations under increasing staffing and Station 2 automation. Source: CASP and authors.

4. Discussion

Manufacturing in SME has historically progressed through incremental changes, moving from hand tools to machine-assisted operations as a pragmatic response to cost, skills, and survival constraints. The present results matter because they outline a feasible pathway for SMEs to introduce selective machine-supported operations without assuming a

fully industrialized plant from the outset. The simulation results also show that technology substitution should be treated as a targeted intervention. It should be justified by measured process data and aligned with the active bottleneck of the line.

This study breaks a paradigm; it cannot accelerate production scale unless high technology is included. This is possible if the logic is applied: automate, standardize, and integrate.

The first implication relates to DfMA, where standardization is a core principle because it reduces the number of components and the diversity of materials. This, in turn, reduces the complexity of the process, costs, and assembly times. In this study, the baseline simulation adopted a standardized production logic. The comparison across manual, semi-automated, and automated scenarios therefore emphasized bottleneck behavior, staffing strategies, and the effect of selective automation, rather than isolating the causal effect of standardization alone.

The second implication concerns partial automation. Productivity gains are attainable, but only when automation is deployed at the right station and under a coordinated labor plan. At Station 2, automated fixing and cutting did not increase annual output under the 12-operator baseline because the system remained constrained upstream at Station 1. Once the bottleneck was managed and the staffing adjusted accordingly, the machine utilization was increased, as shown in Figures 9–11. In effect, this supports a clear recommendation: SMEs should avoid automation in isolation. Instead, automation should be introduced together with a redesign of labor allocation, internal logistics, and station capacities.

A third implication is the scaling logic. The proposed plant concept has three specialized lines (walls, roofs, and floors), dual stations, and balanced labor. It provides a stable structure that can absorb demand variability while maintaining a predominantly manual baseline. This supports a staged industrialization pathway that is realistic for SMEs.

A fourth implication is the house scaling. This is a new paradigm called the product platform, because of its capacity to scale from 1X to "n"X multi-panel housing. The experiment was realized on a module 1X scaled to 8X based on a platform with three initial phases: design, library, layout where it was possible to generate a multi-component and the panel platform required for the simulation.

Regarding the automation hypothesis, Station 2 was expected to deliver a more than 30% efficiency improvement by automating two of eight activities in a man–machine setting. The results support Station 2 as a priority because the cutting exhibited greater time variability, therefore a larger improvement margin. The trials relied on the CNC machine's default routing, suggesting that additional gains may be achievable under an industrial implementation. Two practical directions follow: CNC nailing route optimization for fixing and panel optimization router for cutting.

Finally, while annual throughput is a useful planning metric, SMEs also face peaks, variability, and short-term scheduling constraints. The discrete-event simulation framework provides a practical basis for assessing these dynamics, including peak loads, bottleneck persistence, and labor sensitivity. Importantly, it demonstrates that a standardized-component line can operate under a continuous or quasi-continuous logic.

5. Conclusions

This study demonstrated that SMEs can start with the targeted standardization of prefabricated wood panels. The approach uses a panel library and coded kits to enable scalable production, repeatable quality, and a structured workflow for light timber framing. Using a Chilean industrial case, time-study data and discrete-event simulation were combined to evaluate standardized panel production and the effect of selective CNC automation under different staffing configurations. The main conclusions are as follows.

Standardization is the primary enabler of repeatability in SMEs. Structuring production with a panel library and a simple hierarchy (panels–components–modules) stabilizes manual work and reduces variability. It also supports consistent assembly using common electric and pneumatic tools. From an implementation perspective, the approach facilitates rapid training and does not require highly specialized labor for basic panel assembly.

Selective CNC automation increases capacity only when bottlenecks are addressed at the system level. CNC-based fixing and cutting can improve dimensional consistency and reduce fabrication errors. It can also reduce material losses by improving the use of standard board dimensions in modular designs. This reinforces that automation should be deployed as part of a coordinated redesign rather than as a stand-alone upgrade.

The proposed three-line plant concept supports SME-scale growth with realistic resources. Organizing production into specialized lines for walls, roofs, and floors, together with standardized components and balanced labor, enables annual output above 200 houses when staffing increases from 12 to 18 operators. Nevertheless, with selective automation of key tasks in Station 2, the system can increase to 300 houses per year if upstream bottlenecks are prevented.

Academically, it provides tools for future research based on DfMA and the simulation process where (i) anticipating failure is possible when the manufacturing pathway is evaluated, and (ii) balanced investment and workforce thresholds required for each stage of industrialization will be proposed.Another contribution is mathematical modeling to create a manufacturing product platform from 1X to "n"X for scalable housing.

Practically, it provides a reproducible approach of "Platform thinking for construction" to evaluate staged industrialization decisions in SME timber prefabrication. It delivers an implementable pathway for resource-constrained firms: standardize first, solving bottlenecks with labor and layout decisions, and then automate selectively where it relieves the limiting operation.

Future research opportunities may be based on observed bottleneck patterns; candidate interventions include (i) Station 1 with assisted or automated nailing and guidance systems (e.g., lights or lasers) to support accurate layout; (ii) Station 3 with mechanized membrane unwinding and feeding to support stapling; (iii) Station 4 with mechanized support for installation and sealing; and (iv) inter-station transport with straight-line automated handling to reduce transfer time and work-in-process.

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Abbreviations

The following abbreviations are used in this manuscript:

SMEs	Small and Medium Enterprises
AA	Automatic/Automatic
ANID	Agencia Nacional de Investigación y Desarrollo (Chile)
APA	American Psychological Association
BIM	Building Information Modeling
CASP	Centro Avanzado de Simulación de Procesos
CNC	Computer Numerical Control
DfMA	Design for Manufacture and Assembly
LTF	Light Timber Framing
MA	Manual/Automatic
MDPI	Multidisciplinary Digital Publishing Institute
MMC	Modern Methods of Construction
MM	Manual/Manual
SME	Small and Medium-Sized Enterprise
SMEs	Small and Medium-Sized Enterprises
UBB	Universidad del Bío-Bío
WIP	Work-in-Process

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