Design and Fabrication of a Modular Three-Unit Pallet-Based Press for Wood Densification

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A modular pallet-based press was designed and fabricated to integrate preheating, progressive compression, and cooling under restraint for solid-wood densification. Three separately driven units provided an effective pressing length of 950 mm and width of 140 mm per unit. The prototype accommodated a specified workpiece envelope of 110 mm in width, 55 mm in thickness, and 800 mm in length. The compression unit combined a horizontal lower pallet track with an inclined upper track. Thickness-limiting metal molds were introduced after preliminary trials revealed pallet impressions. In the reported application, Scots pine and black poplar were processed at a travel-speed setting of 0.50 m/min to a mold-defined thickness of 20 mm under load. Preheating and cooling involved stationary dwell periods controlled using exposed side-surface temperature readings. Thus, the implemented sequence was intermittent rather than uninterrupted through-feed. Pallet warm-up to 200 °C required approximately 15 min, and one operating session extended to 10 h. For the reference case involving 26.7 mm-thick Scots pine specimens, the calculated in-line residence time was 13.6 min, and the theoretical steady-state throughput of approximately 11.2 specimens/h was consistent with actual production. The documented design and operating sequence provide a basis for further instrumented performance evaluation and process optimization.

DOI: 10.15376/biores.22.1.135-151

Keywords: Wood densification; Machine design; Pallet press; Modular construction; Progressive compression; Thickness-limiting mold; Intermittent operation

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INTRODUCTION

Mechanical densification provides a route for increasing the utilization potential of lower-density wood by reducing its cellular void volume. Its relevance extends from surface-hardened components to more extensively compressed solid wood. The outcome depends on the interaction between wood anatomy and processing conditions rather than compression ratio alone. Recent reviews identify a broad range of densification methods and applications, while also emphasizing the challenges of translating material-level improvements into practical manufacturing processes (Cabral *et al.* 2022; Paul *et al.* 2024). For equipment development, the central issue is how to deliver the required thermal and mechanical history in a controllable and accessible machine configuration.

Wood softening is sensitive to both temperature and moisture content. Lenth and Kamke (2001) experimentally demonstrated moisture-dependent thermal transitions

associated with amorphous wood components. Accordingly, a temperature selected for one material condition cannot be assumed to represent a universal softening threshold. A densification machine must accommodate heating before substantial deformation, controlled reduction of thickness, and subsequent restraint during cooling. These requirements are coupled: changing transport speed also changes contact time, while changes in contact pressure and tooling can affect heat transfer.

The distribution of compression through the thickness is likewise process-dependent. Rautkari *et al.* (2011) investigated how processing conditions influenced the density profile of surface-modified Scots pine. Such work provides a material-level rationale for controlling heating and compression separately, but it does not imply that an adjustable machine automatically produces either a uniform bulk density profile or a prescribed surface layer. Equipment capability and the resulting wood structure must be established at their respective levels of observation.

A second consideration is the distinction between maintaining geometry during processing and stabilizing wood against later moisture exposure. Combined densification and thermo-hydro-mechanical processing have been investigated to address shape recovery (Navi and Heger 2004). More recently, Altgen *et al.* (2026) showed that moisture exposure can reverse part of the temporary property changes in thermo-mechanically densified birch and aspen. Consequently, cooling under restraint is a relevant machine function, but its implementation alone does not demonstrate permanent fixation of the compressed material.

Continuous pressing offers an alternative to performing every operation in a single stationary press. In wood-based panel manufacture, Thoemen and Humphrey (2003) modeled coupled transport, thermal, and mechanical processes in a moving mat. Although panel consolidation differs from compression of solid wood, that work illustrates why a press must be considered as an interacting process system. For solid wood, Sadatnezhad *et al.* (2017) used a continuous panel press with separately adjustable heating and distance-control sections to achieve surface densification. Thus, continuous transport, zoned heating, and progressive gap reduction already have precedents and cannot individually establish novelty for a new prototype.

Scharf *et al.* (2023) subsequently examined a belt press for continuous densification of sawn timber. Their findings linked processing speed and temperature to the resulting surface-density profile and recovery behavior, underlining the importance of contact time. This establishes an important design context: the choice between moving contact and stationary dwell should follow the required treatment history, and a machine with separate drives still requires coordinated material transfer. It is also necessary to distinguish the presence of a through-feed architecture from evidence of uninterrupted movement in a particular operating sequence.

The present work addresses the integration of these requirements in a compact, three-unit pallet-based prototype. Its contribution is the documented combination of separate preheating, inclined-track compression, and restrained-cooling modules with individually adjustable drives and thickness-limiting tooling introduced during commissioning. The study describes the as-built arrangement, manufacturing sequence, control logic, and reported operating observations, and evaluates their engineering implications using transparent dimensional and kinematic calculations. The study focuses on machine development, supported by initial wood-condition data and limited post-conditioning thickness-recovery results. Mechanical and microstructural characterization remain outside its scope, and the implemented intermittent sequence is distinguished explicitly from a fully continuous production mode.

EXPERIMENTAL

Design Basis and Documentation

The prototype was developed under TÜBİTAK project 124O590. The initial design requirements were reconciled with the fabricated machine and the operating procedure used during project implementation. The final technical report, manufacturing photographs, component specifications, and operating information supplied by the project team formed the engineering record. Numerical values were classified as nominal specifications, applied settings, approximate operating observations, or calculations derived from geometry. The operating observations were descriptive and were not a replicated machine-performance dataset; no inferential statistical analysis was performed.

Table 1. Principal Specifications of the Fabricated Prototype

Item	Specification
Process architecture	Three aligned pallet units: preheating, compression, and restrained cooling
Frame dimensions per unit	Approximately 1250 × 650 × 790 mm (length × width × height)
Effective pressing area per unit	950 × 140 mm
Specified workpiece envelope	Up to 800 × 110 × 55 mm (length × width × thickness)
Nominal thermal operating range	20 to 220 °C
Adjustable pallet travel-speed range	0.30 to 1.50 m/min
Reported travel-speed setting	0.50 m/min in all three units during movement
Pallet-drive motors	Two per unit; six in total; 0.75 kW and 1450 r/min per motor
Pallet-drive transmission	Double-reducer arrangement for speed reduction and torque increase
Summed pallet-drive motor ratings	1.50 kW per unit; 4.50 kW for the three units
Motor speed controller	1.5 kW frequency drive per unit
Resistance heaters	Four per heated unit (2 upper, 2 lower); eight total; 2.5 kW each
Installed heating capacity	10 kW per heated unit; 20 kW in total
Hydraulic pump motor	Rated power: 4 kW
Cooling-water circulation pump	Rated power: 0.37 kW
Sum of listed component ratings	28.87 kW (arithmetic sum; see note)
Hydraulic cylinders	Two per unit; 75 mm bore and 110 mm outer diameter
Nominal cylinder force	Approximately 49 kN per cylinder (5 metric ton-force)
Compression endpoint in the application	20 mm under load, defined by metal stops

Specification ranges differ from the applied operating conditions. Power entries are component ratings; 28.87 kW is their arithmetic sum, not measured machine electrical input or energy consumption.

The design objectives were to separate thermal preparation from the main compression stage, reduce thickness progressively during transport, and retain the compressed geometry while cooling. Additional requirements concerned independently

adjustable drives, access for adjustment and maintenance, and handling of short solid-wood specimens. The specified workpiece envelope was 110 mm in width, 55 mm in thickness, and 800 mm in length. These are accommodation limits of the prototype, not verified densification limits for every species and thickness within that envelope. Table 1 summarizes the principal specifications.

Mechanical Architecture and Material Selection

The three units were placed along a common material-transfer axis. Each unit comprised a steel frame, upper and lower pallet assemblies, two 0.75 kW pallet-drive motors with double-reducer transmissions, and two hydraulic cylinders acting on the adjustable upper assembly. The six pallet motors had a combined nominal rating of 4.50 kW. The first unit provided preheating, the second produced the main thickness reduction, and the third maintained restraint while removing heat. The completed machine is shown in Fig. 1. This arrangement distributed process functions among modules while retaining a common pallet-based transport principle.



Fig. 1. Fabricated three-unit pallet-based press, showing the aligned modules, drive assemblies, hydraulic cylinders, and external control cabinet

The specified pallet pressure blocks were manufactured from ST52 steel, with ST37 steel used for structural and connecting components and heat-treated AISI 1040 steel for shafts. The design documentation specified 51 pressure blocks per unit, a 19.05 mm (3/4 in) chain pitch, and 26-tooth drive sprockets. The linked blocks formed an articulated track around the return regions and a closely spaced contact surface along the pressing region. Adjustable chain-tensioning mechanisms were incorporated to accommodate assembly adjustment and service-related slack. Figure 2 shows the principal drive components and the pallet arrangement.

The mechanical configuration used a horizontal lower track in the compression unit and an upper track inclined toward a smaller outlet gap. This provided progressive closure along the direction of travel. The hydraulic slide arrangement allowed the upper assembly

to be positioned for different workpiece and mold geometries. The frame and pressing components were developed as a manufacturable assembly; no finite-element stress field, measured frame deflection, or fatigue-life result was available for this study. Therefore, material designations describe the construction rather than establish quantified structural margins.

Computer-aided design was performed using AutoCAD 2024 (Autodesk Inc., San Francisco, CA, USA) and SOLIDWORKS 2023 (Dassault Systèmes Inc., Vélizy-Villacoublay, France) to develop the overall arrangement and inspect component compatibility. Fabrication and assembly were undertaken with Sofuoğlu Machine Automation and Industrial Trade Ltd. Co. (Sakarya, Turkey). The documented sequence comprised material procurement, welded frame fabrication, machining of pressure blocks and drive components, installation of cylinders and slide systems, assembly of geared drives, preparation of heating and cooling provisions, and electrical integration. The modules were then aligned along the common transport axis. Commissioning checks addressed chain tension, shaft and sprocket alignment, pallet parallelism, slide clearances, hydraulic movement, coolant leakage, sensor placement, and motor direction.

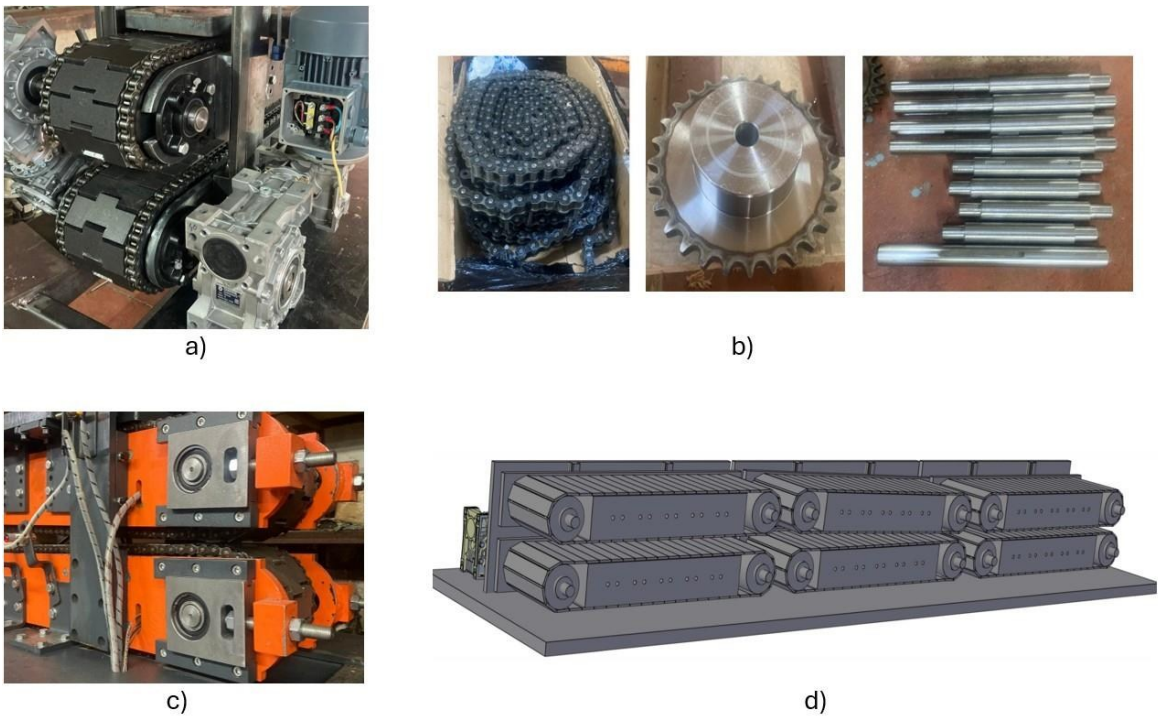
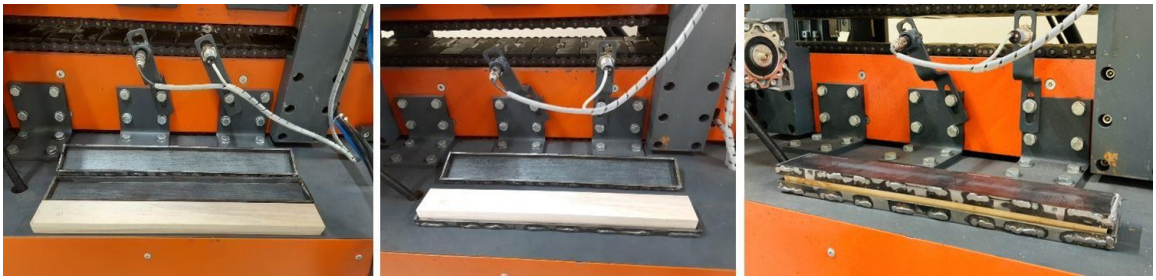


Fig. 2. Pallet and drive system: (a) pallet assembly and geared drive; (b) chain, sprocket, and shaft components; (c) chain-tension adjustment; and (d) original computer-aided design model of the pallet assemblies

Hydraulic Loading and Thickness-limiting Tooling

The hydraulic installation comprised a pump driven by an electric motor rated at 4 kW, a reservoir, directional and pressure-control valves, hoses, and six cylinders, with two cylinders associated with each unit. The nominal force specified for each cylinder was approximately 49.0 kN (5 metric ton-force). This component rating should not be interpreted as the force applied to the wood specimens. Hydraulic operating pressure and force-time records were not available for the present analysis.

Preliminary trials without the final tooling produced localized pallet impressions on the wood surfaces. Therefore, thickness-limiting molds manufactured from ST52 steel were introduced to provide an intervening contact surface and a mechanical stop defining the target wood thickness. The molds accompanied the specimens through processing and formed part of both the load-transfer and heat-transfer interfaces. An exposed side region of the wood remained visible to the temperature sensor. The project molds are shown in Fig. 3, and the mold-defined wood-thickness endpoint was 20 mm under load. No dimensional changes were observed in the molds during the reported densification trials.



a) b) c)

Fig. 3. Thickness-limiting metal molds used in the project: a) the specimen and tooling before assembly; b) placement of the specimen and c) assembled tooling; mechanical stops defined a 20 mm wood thickness under load

The project application used the machine's full-capacity hydraulic setting, with the compression endpoint determined by the mold stops. This operational description was not converted to a measured pressure. Once the stops contact, part of the applied load can be carried by the metal tooling; therefore, dividing a nominal actuator force by the wood area would not establish the actual stress in the specimen. The reported 20 mm value describes a geometric constraint during loading and is not a measurement of final thickness after unloading or conditioning.

Heating, Cooling, and Temperature Measurement

Electrical resistance heaters supplied heat to the first and second units through the upper and lower contact assemblies. Each heated unit contained four heaters (two upper and two lower), each rated at 2.5 kW, giving 10 kW per heated unit and 20 kW in total. In each of the upper and lower pallet assemblies, one heater was positioned along the upper straight run and the other along the lower straight run. The curved return sections were outside the directly heated regions. During warm-up, the pallet drives were operated to circulate the blocks through the heated sections, ensuring that all blocks were exposed to heating. Heater support plates were specified as Hardox steel in the project documentation. Solid-state relays controlled electrical power to the heaters. Glass-wool and mica-based insulation elements were used to limit heat transfer into adjacent structural regions. Figure 4 shows the documented heater arrangement, insulation, and electrical connections. The third unit incorporated water-circulation channels in its cooling/contact assembly so that heat could be removed while the specimen remained restrained. The cooling-water circulation pump serving the third unit was rated at 0.37 kW.



a) b) c)

Fig. 4. Heating-system construction: (a) resistance-heater support arrangement; (b) insulation within the assembly; and (c) heater connections in the upper and lower unit regions

Temperature was monitored using TS01 non-contact infrared sensors (SEN0264, DFRobot, Shanghai, China) with a 4 to 20 mA analog output and a nominal measurement range of −70 to +380 °C. The sensors were positioned *ca.* 50 to 100 mm from the exposed lateral wood surface at mid-thickness height. The viewed region was not covered by the metal molds. Sensor outputs were converted to temperature using an equation programmed into the control system, and temperature indications were checked by comparison with a separate analog temperature-measuring device. The measured variable, T_{side}, represented the side-surface temperature. No internal thermocouple was installed. Transfer from the preheating unit was initiated at approximately T_{side} = 150 °C, and discharge after cooling occurred at T_{side} < 90 °C. These values served as operational control thresholds.

Control System and Implemented Operating Sequence

The control cabinet housed the operator interface, programmable control components, solid-state relays, motor frequency drives, electrical protection devices, and hydraulic valve connections (Fig. 5).



a) b) c)

Fig. 5. Electrical and control installation: (a) external cabinet and operator interface; (b) internal arrangement; and (c) protection, relay, and drive components

The interface provided automatic and manual operation. Temperature setpoints and motor-frequency settings could be entered for the separate units, and manual commands allowed individual drive and hydraulic functions to be checked during commissioning. Position/motion sensing and temperature information were used to coordinate transfer. An emergency-stop button and electrical protection components were provided; their inclusion is reported as an equipment feature, without assigning a certified safety performance level.

The prototype trials were conducted using Scots pine (*Pinus sylvestris* L.) and black poplar (*Populus nigra* L.) specimens. Before pressing, all specimens were conditioned at 20 ± 2 °C and 65 ± 3% relative humidity. The mean moisture contents before pressing were 12.1% for Scots pine and 11.6% for black poplar. The air-dry densities of the untreated control specimens were 0.553 and 0.391 g/cm³, respectively. All reported moisture content and density values represent the means of 10 specimens (n = 10) for each species. The specimens measured 47 mm in width (tangential direction) and 400 mm in length (longitudinal direction). Compression was applied in the radial direction, with initial thicknesses of 26.7 and 40 mm corresponding to nominal compression ratios of 25% and 50%, respectively. Both configurations used thickness-limiting metal molds defining a target wood thickness of 20 mm under load. The operating sequence combined stationary thermal dwell with moving compression. The initial thicknesses and mold-defined stopping distance specified the intended compression levels.

In the first unit, the pallet temperature was set to 200 °C, and specimens remained stationary until the exposed lateral wood surface at mid-thickness reached approximately 150 °C. The stationary preheating dwell ranged from approximately 4 to 6 min. The shortest dwell, approximately 4 min, was observed for Scots pine specimens with an initial thickness of 26.7 mm, while the longest dwell, approximately 6 min, was observed for black poplar specimens with an initial thickness of 40 mm. Transfer and compression were then performed with the same travel-speed setting, 0.50 m/min, in the participating units. The second unit operated at a process temperature setting of 150 °C without an intentional stationary dwell. At the 0.50 m/min travel-speed setting, the calculated passage time of a complete 420 mm-long mold through the 950 mm effective compression length was 2.74 min, defined from leading-edge entry to trailing-edge exit. In the third unit, specimens remained stationary under restraint for approximately 2 to 3 min until the side-surface discharge criterion was satisfied. The first- and third-unit times refer exclusively to stationary dwell and exclude movement.

Each 400 mm-long specimen was processed in a 420 mm-long mold. A new mold entered the first unit when the preceding mold resumed movement after reaching the preheating transfer criterion, allowing operations on successive specimens to overlap. Sufficient molds were available. The timing analysis used a reference case involving Scots pine specimens with an initial thickness of 26.7 mm, a stationary preheating dwell of 4 min, and a stationary cooling dwell of 2 min.

Independent drive adjustment was a feature of the architecture, but unequal unit speeds were not evaluated in the reported application. Equal travel-speed settings were used when transferring material between the units. The implemented process was therefore an intermittent, sequential operation on a through-feed pallet arrangement. Table 2 specifies the sequence, and Fig. 6 documents its physical implementation.

Table 2. Applied Operating Sequence and Temperature Criteria

Unit	Thermal Condition	Movement and Time
1. Preheating	Pallet setting: 200 °C; transfer at T_{side} ≈ 150 °C	Stationary dwell: approximately 4 to 6 min; travel at 0.50 m/min
2. Compression	Process setting: 150 °C; mold stop: 20 mm	Complete-mold passage: 2.74 min at 0.50 m/min; no intentional dwell
3. Restrained cooling	Water-circulated cooling; discharge at T_{side} < 90 °C	Stationary dwell: approximately 2 to 3 min; travel at 0.50 m/min

T_{side} is the infrared reading on the uncovered lateral wood surface at mid-thickness height. Dwell periods exclude movement. The approximate preheating dwell limits were 4 min for 26.67 mm Scots pine specimens and 6 min for 40 mm black poplar specimens.

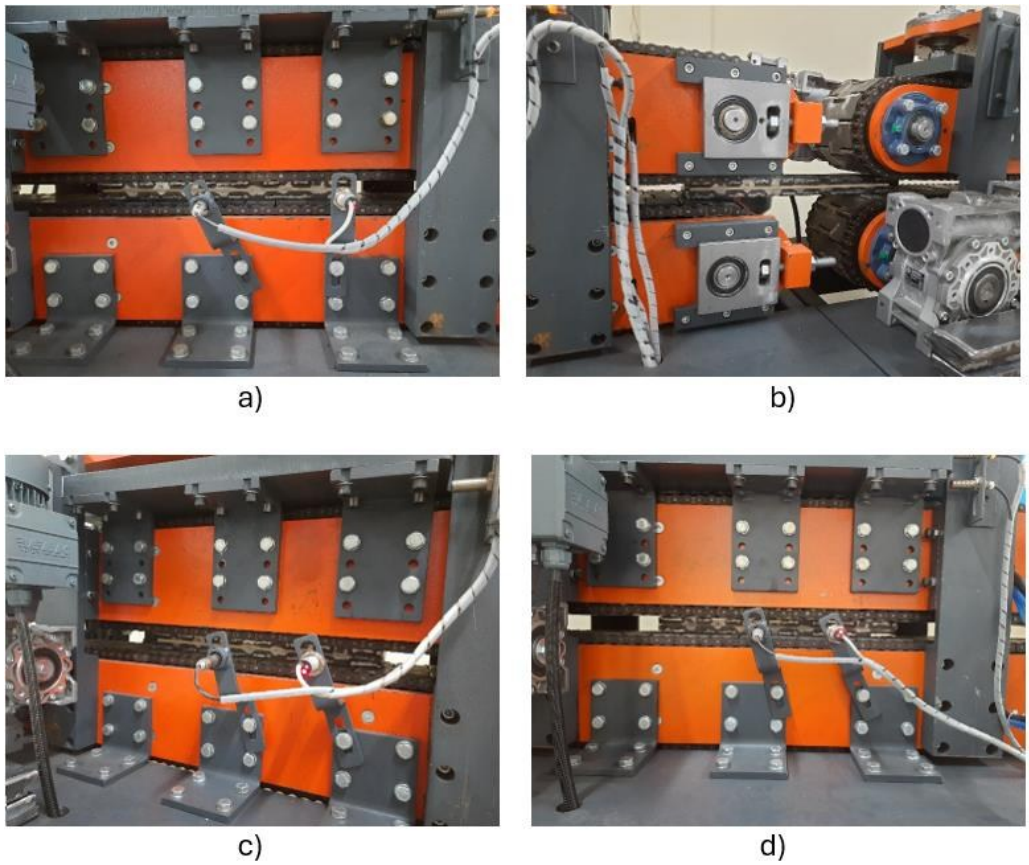


Fig. 6. Mold-assisted processing in the prototype: (a) preheating in the first unit; (b) transfer toward the second unit; (c) progressive compression in the inclined-track unit; and (d) restrained cooling in the third unit

Engineering Evaluation

The evaluation combined as-built documentation, descriptive commissioning observations, and calculations requiring only the supplied dimensions and operating settings. The nominal compression ratio, CR (%), was calculated as,

$$CR = 100(h_o - h_{stop}) / h_o \quad (1)$$

where h_o is the initial wood thickness (mm) and h_{stop} is the mold-defined wood thickness under load (20 mm). After processing and removal from the molds, the specimens were

conditioned at 20 ± 2 °C and 65 ± 3% relative humidity before thickness measurement. Post-conditioning spring-back (SB, %) was calculated as,

$$SB = 100(h_c - h_{stop}) / h_{stop} \quad (2)$$

where h_c is the thickness measured after conditioning (mm). The reported SB represents thickness recovery up to the conditioned state. The kinematic travel time, t_{travel} (min), for a material point to traverse an effective track length was calculated as,

$$t_{travel} = L_{eff} / v \quad (3)$$

where L_{eff} is the effective pressing length (m) and v is the applied travel-speed setting (m/min). Equation 3 assumes uninterrupted movement over that length and excludes stationary dwell, entry/exit details, inter-unit distances, and acceleration. Complete-mold passage through the compression unit, defined from leading-edge entry to trailing-edge exit, was calculated as,

$$t_{comp} = (L_{eff} + l_{mold}) / v \quad (4)$$

where t_{comp} is the complete-mold passage time (min), L_{eff} is the effective compression length (0.950 m), l_{mold} is the mold length (0.420 m), and v is the applied travel-speed setting (0.50 m/min). Total in-line residence time, from mold leading-edge entry to trailing-edge exit, was calculated as,

$$t_{line} = (L_{line} + l_{mold})/v + t_{preheat} + t_{cool} \quad (5)$$

where t_{line} is the residence time (min), L_{line} is the entry-to-exit distance (3.370 m), and $t_{preheat}$ and t_{cool} are the stationary preheating and cooling dwells (min). The reference planes were the beginning of the first and the end of the third straight working run. A new mold entered when the preceding mold resumed movement after preheating. The interval between successive mold entries was calculated as,

$$\Delta t = d_{entry}/v + t_{preheat} \quad (6)$$

where Δt is the entry interval (min) and d_{entry} is the leading-edge travel distance from entry to the stationary preheating position (0.685 m). With one specimen per mold, theoretical steady-state throughput was calculated as,

$$Q_{th} = 60/\Delta t \quad (7)$$

where Q_{th} is throughput in specimens per hour and 60 converts minutes to hours. Reference calculations concerned Scots pine specimens with an initial thickness of 26.67 mm, stationary preheating and cooling dwells of 4 and 2 min, sufficient molds, and no additional preparation or handling delays. The theoretical throughput was consistent with actual production under these conditions.

RESULTS AND DISCUSSION

Realization of the Modular Process Architecture

The fabricated prototype integrated preheating, progressive compression, and cooling under restraint along one aligned pallet route. Separating these functions allowed the two heated units and the cooling unit to maintain distinct process roles. The effective contact dimensions of 950 mm × 140 mm corresponded to a nominal track area of 0.133 m² per unit. The distinction between this area and the actual wood-contact area is important:

workpiece dimensions, tooling, and progressive engagement determine how much of the track participates in load transfer at any instant.

The specified maximum wood width of 110 mm was smaller than the 140 mm pressing width, and the 800 mm length limit was shorter than the 950 mm effective pressing length. These dimensions define the specified accommodation envelope of the prototype. They do not establish that all workpieces within this envelope can be processed using the same thermal dwell schedule as the specimens used here, which measured 47 mm in width, 400 mm in length, and 26.7 or 40 mm in initial thickness. Moreover, the nominal 20 to 220 °C thermal range and 0.30 to 1.50 m/min speed range should not be interpreted as a fully mapped load-dependent operating envelope.

The principal integration result was the ability to use stationary thermal stages and moving thickness reduction within the same machine. This is a meaningful distinction from simply dividing a continuous line into named zones. In the present arrangement, the selected sequence used dwell to satisfy temperature criteria while retaining the possibility of adjusting each drive independently. The architecture consequently supported process separation, whereas the realized operating mode remained dependent on coordination among modules and on the chosen dwell schedule.

Tooling Adaptation and the Compression Endpoint

Localized impressions observed in preliminary trials identified the contact interface as an important commissioning issue. The introduction of thickness-limiting metal molds provided a practical adaptation that addressed direct pallet marking and defined a common stopping thickness. Because impression depth or surface topography was not quantified before and after the change, the evidence supports the adoption and use of the tooling rather than a numerical improvement in surface quality. The change also means that mold-free operation should not be presented as an established characteristic of the reported application.

Equation 1 gave approximately 25.0% nominal compression for the 26.7 mm starting thickness and 50.0% for the 40 mm starting thickness. The corresponding intended thickness reductions were 6.67 and 20 mm. Both configurations used the same 20 mm stop. This allowed the nominal compression ratio to be changed through the initial specimen thickness without changing the target wood-thickness endpoint. However, the stop controls displacement while the specimen is restrained; it does not establish the thickness retained after discharge.

Table 3. Post-conditioning Spring-back and Calculated Thickness

Wood species	Nominal compression ratio (%)	Spring-back (%)	Calculated conditioned thickness (mm)
Scots pine	25	4.74 (0.49)	20.95 (0.10)
	50	18.75 (1.30)	23.75 (0.26)
Black poplar	25	6.59 (0.65)	21.32 (0.13)
	50	17.61 (1.37)	23.52 (0.27)

Values are means, with standard deviations in parentheses (n = 10 per group).

Post-conditioning spring-back increased with nominal compression ratio in both species (Table 3). For Scots pine, mean spring-back was 4.7% at 25% nominal compression and 18.8% at 50%; the corresponding values for black poplar were 6.6% and 17.6%. Thus,

both species showed greater thickness recovery at the higher compression level under the applied processing conditions. The calculated mean conditioned thicknesses ranged from approximately 20.9 to 23.8 mm. These results provide preliminary quantitative evidence that thickness reduction was retained after conditioning, while confirming that the 20 mm mold opening should not be interpreted as the final conditioned product thickness.

The thickness-limiting molds alter the load path when their stops engage. Before contact, the load transmitted through the mold faces is resisted mainly by the wood. After contact, the wood and stops carry load in parallel, with the distribution governed by their relative stiffnesses, contact conditions, and tooling deformation. The wood therefore remains loaded, although the stops may carry part of any additional actuator load without a proportional increase in wood stress. Neither the force transmitted to the tooling nor its distribution between the wood and stops was measured. The summed nominal actuator force (approximately 98.1 kN per unit) therefore cannot be treated as the specimen force or divided by the wood-contact area to determine actual compressive stress. The 20 mm stop opening defines the intended final thickness under load, while the nominal compression ratios describe the corresponding thickness reductions. These geometric parameters establish neither the magnitude and uniformity of wood stress nor the force needed to achieve a given compression ratio. Without force measurements, pressure requirements also cannot be compared quantitatively between species or pressing systems. The molds also affect thermal boundary conditions through their thermal mass and contact interfaces. These effects were not quantified and, together with load sharing, should be examined in future instrumented tests.

Thermal Dwell and Transport-time Interpretation

The approximately 15 min warm-up to the 200 °C pallet setting was conducted with the pallets in motion. Circulation carried all pallet blocks through the heated straight sections of the upper and lower assemblies, including those passing through the return regions. This operating procedure promoted more even heat exposure across the blocks. The reported warm-up time represents an operating observation of machine preparation. The subsequent 4 to 6 min specimen-preheating dwell and 2 to 3 min cooling dwell were governed by the exposed side-surface temperature criteria. The operating observations showed that thicker specimens required longer preheating and that Scots pine reached the transfer criterion sooner than black poplar.

At the applied travel-speed setting of 0.50 m/min, a material point traversed the 0.95 m effective track length in a calculated 1.90 min. Accounting for the 0.420 m mold length gave a complete-mold passage time of 2.74 min through the compression unit, measured conceptually from leading-edge entry to trailing-edge exit. For the reference case involving 26.67 mm-thick Scots pine specimens, the calculated total moving time was 7.58 min. Adding the 4 min preheating and 2 min cooling dwells gave an in-line residence time of 13.6 min. The compression-unit passage was already included in the total moving time and was not added separately.

Successive molds entered at a calculated interval of 5.37 min, comprising 1.37 min of movement to the preheating position and a 4 min stationary dwell. The corresponding theoretical steady-state throughput was approximately 11.2 specimens/h, which was consistent with actual production under the reference operating conditions. Sufficient molds were available, and mold preparation, loading, and unloading introduced no additional line delays. Preheating governed the entry interval for this reference case

involving Scots pine specimens with an initial thickness of 26.67 mm and stationary preheating and cooling dwells of 4 and 2 min, respectively.

The side-surface reading, T_{side}, does not resolve the internal temperature distribution of the specimen. During heating, internal regions may warm more slowly than the heated contact surfaces, whereas during cooling the core may retain heat after external regions have cooled. The exposed lateral surface and mold-contact surfaces also experience different thermal boundary conditions, preventing a fixed relationship between T_{side} and core temperature from being assumed. The moisture dependence of wood softening further limits their interpretation as universal thresholds (Lenth and Kamke 2001). Paired surface and internal measurements in a dedicated validation setup would help quantify thermal lag.

Table 4. Documented and Derived Engineering Quantities

Quantity	Value	Basis
Pallet warm-up to 200 °C	Approximately 15 min	Operating observation with pallet circulation
Nominal compression ratios	Approximately 25% and 50%	Calculated from initial thickness and 20 mm stop
Effective track area per unit	0.133 m²	Calculated from 0.95 × 0.14 m
Material-point travel over one effective track	1.90 min	0.950/0.50; Eq. 3; excludes dwell
Complete-mold passage through the compression unit	2.74 min	(0.950 + 0.420) / 0.50; Eq. 4; no stationary dwell
Combined stationary thermal dwell	Approximately 6 to 9 min	Sum of reported first- and third-unit dwell ranges
Stationary preheating and cooling, reference case	4 min and 2 min	First and third units, respectively
Total in-line moving time	7.58 min	(3.370 + 0.420) / 0.50; excludes stationary dwell
In-line residence time, reference case	13.58 min	7.58 + 4 + 2; Eq. 5; includes compression-unit passage
Successive mold-entry interval, reference case	5.37 min	0.685 / 0.50 + 4; Eq. 6
Maximum simultaneous in-line occupancy, reference schedule	3 molds	Predicted from the overlapping timing schedule
Theoretical steady-state throughput, reference case	Approximately 11.17 specimens/h	60/5.37; Eq. 7; one specimen per mold
Actual steady-state throughput, reference case	Approximately 11.17 specimens/h	Reported production under the reference conditions; consistent with theoretical throughput
Summed nominal actuator force per unit	Approximately 98.1 kN	Two cylinders, each nominally rated at approximately 49.0 kN; not measured wood load
Sum of specified pallet-drive motor ratings	4.50 kW	Six 0.75 kW ratings; excludes heaters and auxiliary systems
Extended operating session	10 h	Reported operation; not a reliability qualification

Relationship to Existing Densification Equipment

The comparison with previous machinery must distinguish shared principles from the particular implementation. Sadatnezhad *et al.* (2017) already demonstrated upper and lower heat transfer, progressive gap regulation, and multiple adjustable sections in a continuous panel press used for solid-wood surface densification. The present prototype therefore does not establish those principles for the first time. Its distinguishing arrangement is the separation into three compact pallet modules, combined with individually adjustable drives, stationary thermal dwell in the implemented sequence, and a mold-defined compression endpoint.

Scharf *et al.* (2023) investigated the dependence of continuous belt-press processing on speed, temperature, and compression ratio. Their results reinforce the need to evaluate thermal contact time when selecting a transport strategy. In the present prototype, the stationary dwell stages enabled additional thermal exposure without reducing the travel setting used during transfer. However, this comparison does not demonstrate superior productivity: the machines operated with different material dimensions, thermal histories, and densification objectives. Their reported feed speeds cannot be directly converted into an efficiency ranking for the present discrete-workpiece application.

Compared with performing heating, compression, and cooling in the same stationary press, the modular arrangement separates the hardware assigned to each function. In the reported sequence, operations on successive molds overlapped across the modules. The arrangement also permits individual units to be modified, while comparative gains in throughput or maintenance time remain to be quantified. The actual benefit depends on the scheduling of unit occupancy, mold handling, transfer distances, and the slowest processing stage. Sandberg *et al.* (2017) emphasized the need to consider environmental impacts during the development of wood-modification processes; however, the environmental implications of the present prototype require further assessment, as no direct environmental impact analysis was conducted in this study.

Operating Evidence, Limitations, and Further Development

One application session extended to 10 h, providing descriptive evidence that the integrated prototype could be used over an extended work period. This does not mean that every specimen moved continuously for 10 h, because stationary dwells were part of normal operation. Nor does the session provide a quantified duty cycle, availability, failure rate, or component life. The result is appropriately interpreted as an operating observation supporting practical integration of the machine functions.

The evidence also separates restrained cooling from permanent material stabilization. Maintaining the mold-defined thickness during cooling is a machine function; resistance to moisture-driven recovery is a material outcome requiring separate tests. The distinction is consistent with the temporary property changes documented by Altgen *et al.* (2026). Table 3 provides limited post-conditioning thickness-recovery data. These results do not establish long-term resistance to moisture-driven recovery, improved performance relative to other pressing systems, or preservation of cellular structure.

The main limitations concern metrology and component-level reproducibility. Cylinder pressure, actual contact force, frame deflection and bolted-joint displacement, independent speed measurements, quantitative sensor calibration data, mold tolerances, and coolant flow were not available as measured datasets. Consequently, the study cannot establish a structural safety factor, a thermal balance, a closed-loop control accuracy, or a

statistically supported output tolerance. The construction record and operating description nevertheless identify the subsystems and boundary conditions that an instrumented evaluation would need to address.

For future structural development, the frame and bolted connections should be assessed under repeated hydraulic loading, particularly at the cylinder mounts and upper-pallet supports. Potential improvements include local stiffeners or load-spreading plates where required, controlled bolt preload, suitable anti-loosening provisions, and alignment checks to limit eccentric loading. These measures should be evaluated through repeated loading–unloading tests at documented hydraulic pressures and operating temperatures, with relative displacement measured at critical mounting points. The results would guide reinforcement and connection refinement.

Further tooling development should assess the adhesion of wood extractives to the wood-contacting mold surfaces and the associated cleaning requirements. Comparative tests could evaluate uncoated molds, polytetrafluoroethylene (PTFE)-coated molds, and alternative low-adhesion surfaces under matched processing conditions. Evaluation criteria should include residue accumulation, demolding force, cleaning frequency, wood-surface defects, and processing time.

The listed component ratings comprised 4.50 kW for the six pallet-drive motors, 20 kW for the eight resistance heaters, 4 kW for the hydraulic pump motor, and 0.37 kW for the cooling-water circulation pump. Their numerical sum was 28.9 kW. This sum describes component ratings and does not establish the electrical input or energy consumption of the complete machine. Instantaneous electrical power and energy consumption were not measured in this study.

Further process characterization should include independent verification of travel speed under load, measurements of actuator pressure and load sharing between the wood and mold stops, paired surface and internal temperature measurements using a suitable validation setup, and wood thickness immediately after release. Production monitoring should extend the capacity assessment to different wood species, initial thicknesses, and longer operating periods, while recording loading, unloading, mold preparation, and stoppage durations separately. Future electrical measurements should cover the complete machine, including the heaters, pallet drives, hydraulic pump motor, cooling-water circulation pump, controls, and associated drive losses. These measurements would support a sound comparison with stationary presses and guide further development toward uninterrupted through-feed operation.

CONCLUSIONS

1. A three-unit pallet-based prototype was designed and fabricated to combine separate preheating, progressive compression, and cooling under restraint. Each unit provided an effective pressing length of 950 mm and width of 140 mm, with an independently adjustable drive.
2. The implemented procedure used stationary preheating and cooling dwells, together with moving compression and equal travel-speed settings of 0.50 m/min. It was an intermittent sequential process rather than uninterrupted movement through all three units.

3. Thickness-limiting metal molds were introduced after preliminary trials revealed pallet impressions. A common 20 mm wood-thickness stop corresponded to nominal compression ratios of approximately 25% and 50% for initial thicknesses of 26.7 and 40 mm. These values described compression under load, not retained thickness after unloading.
4. The reported observations included approximately 15 min of pallet warm-up to 200 °C, stationary preheating, and cooling dwells of 4 to 6 min and 2 to 3 min, respectively, and one operating session of 10 h. For the reference case involving 26.7 mm-thick Scots pine specimens, the calculated in-line residence time was 13.6 min, and the theoretical steady-state throughput of approximately 11.2 specimens/h was consistent with actual production. Temperature criteria were based on exposed side-surface infrared readings rather than internal wood temperatures.
5. The fabricated prototype demonstrated the practical integration of preheating, progressive compression during transport, and cooling under restraint in three separately driven pallet units. The documented construction and operating observations provide a basis for further instrumented evaluation and optimization of machine performance.

ACKNOWLEDGMENTS

This work was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under the 1005 Program, Project No. 124O590. The authors acknowledge the fabrication and assembly support provided by Sofuoğlu Machine Automation and Industrial Trade Ltd. Co.

Conflict of Interest

A patent application relating to the developed machine has been filed with the Turkish Patent and Trademark Office (Application No. 2024/019277), and examination is ongoing. There is no conflict of interest.

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Article submitted: September 9, 2026; Peer review completed: October 17, 2026; Revised version received: October 21, 2026; Accepted: October 28, 2026; Published: November 9, 2026.
DOI: 10.15376/biores.22.1.135-151