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State-of-the-Art of Utilizing the Hygrocopicity and Resulting Dimensional Change of Wood for the Moisture-Induced Joining of Wooden Elements

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Abstract

Timber has regained popularity in construction in recent years due to its ecological benefits. The connection methods used in this study play a vital role in the sustainability of structures and materials. Monomaterial timber connections are sustainable alternatives to metal fasteners and adhesives commonly used in construction. Wood is an anisotropic material with dimensional changes resulting from changes in atmospheric conditions. Understanding and accounting for this property are crucial for the longevity and functionality of wooden structures. The cumulative knowledge of wood´s material characteristics and its use in design, construction, and human culture can be defined as wood culture developed through artists' and craftsmen's experiences, science, and industry. The development of various techniques by artisans to leverage the dimensional change in wood to join timber elements is a major contribution to wood culture. In contrast, until now, the timber industry has mainly focused on limiting or controlling these changes in standardized production and has neglected their use for joining timber elements. However, technological advances have changed dramatically. The digital manufacturing and analysis of wood structures have the potential to guide machine tools and may allow the integration of dimensional changes, especially in the design and construction of timber joints. This study explores the state-of-the-art

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utilization of dimensional changes in timber to join elements in craft, material science, and industrial production. The potential of techniques utilizing this behavior for innovation in modern design and construction and their implications for wood culture were examined. Research gaps and avenues for further research are identified.

Keywords

densified wood – dimensional change – timber construction – timber technology – wood connectors – wood – wood joints

1 Introduction

Transitioning to a circular bio-based economy is crucial for a sustainable future (van der Lugt & Harsta 2020). The building industry plays a major role and has a high potential for reducing resource consumption. Timber is considered a promising solution for sustainability and CO_2 emission reduction because of its low embodied energy, carbon storage capacity, and recyclability (Kolb 2008). Furthermore, cascading allows multiple reuse and recycling (van der Lugt & Harsta 2020).

Wooden architecture has become popular among architects, construction companies, and clients in recent years because of its ecological and constructional advantages. In addition, the creation of engineered wooden products (EWP) has not only changed the face of timber construction. However, it has also expanded the construction possibilities of timber architecture (Buri & Weinand 2011), further increasing its popularity (Sotayo *et al.* 2020). Timber joining has always been a driving force in timber construction (Tang & Chilton 2019), but connectors made from non-bio-based and composite materials are often used for economic reasons, making recycling and reuse challenging, and the adhesives used in EWP further complicate recycling (Sotayo *et al.* 2020).

1.1 *Timber Joints*

Joints are the central elements in wooden constructions. They ensure the interaction of elements, structural integrity, and the tectonic expression of structures. They have evolved in response to changing conditions and demands (Messler 2006) and are closely linked to developing new tools (Gerner 2000). Computational design and manufacturing tools enable the integration of material-specific parameters into design and construction (Kolarevic & Klinger 2013), empowering designers to utilize the material properties of timber (Allner & Kroehnert 2019). The easy machinability of wood makes it an ideal material for digitally controlled woodworking machinery; therefore, the timber industry is well-equipped with such machinery (Buri & Weinand 2011). Timber joints typically rely on form closure (Apolinarska 2018) or form fit, which enables them to transfer mechanical forces solely through geometrical interference (Messler 2006). However, although a precise fit is beneficial for the structural capability of the connections, it affects the ease of assembly. Moreover, wood joints serve functional purposes and contribute to the cultural identity and artistic expression of different woodworking traditions. Different cultures and regions have developed unique joint styles that often reflect their architectural and design preferences (Zwerger 2015). They showcase the skills, creativity, and ingenuity of woodworkers throughout history while preserving the heritage of woodworking techniques and designs for future generations.

1.2 *Material Properties and Their Use in Crafts and Industry*

Wood is an anisotropic material that consists of naturally grown tissues. Its structure is mainly determined by cells, which are mainly composed of cellulose fibers and lignin. Each tree is unique because the composition and distribution of cells differ between species and individual trees. Each species has adapted to local conditions, such as atmospheric conditions, weather, and fauna; as a result, timber is a bespoke material for every ecosystem (Correa *et al.* 2019)

Knowledge of the characteristics of the anisotropic structure of wood and the application of its specific properties in structures is rooted in craft (Schindler 2009). From the source of the material, the design of the structure and selection of the appropriate stock for fabrication and assembly were carried out by artisans, resulting in an integrated design process. Artisans always had a different conception of the relationship between matter and form; rather than commanding it to receive a form, they teased it out of an active material (DeLanda 2004). Their knowledge is derived from working with materials (Ingold 2007). They could compensate for differences in quality through variations in the application of tools (Smith 1981).

During the Stone Age, the first forked posts were produced to resemble the natural forks traditionally used in construction, following design principles in nature. This gradually led to the invention of new techniques to join elements, from wooden pegs to mortise and tenon joints to the highly specialized carpentry of Japanese master artisans. To master the trade, carpenters had to acquire the knowledge and skills required to produce 200–400 joints. Knowledge of the peculiar characteristics of the material is a prerequisite to processing it appropriately (DeLanda 2004; Zwerger 2015).

The development of industrial production has changed the way we work with wood because machines are not designed to process inhomogeneous materials. In the 1940s, a rapid wave of development of various wood-based materials followed the invention of waterproof gluing. These developments were motivated to eliminate irregularities in natural materials and create homogeneous building products. Mass timber was standardized by developing a system of classes based on structural and aesthetic properties using machine lumber sorting in the late 1970s. This development was supported by the invention of waterproof adhesives, resulting in many panel-shaped wooden materials. These newly engineered wooden products (EWP) in plate formats with homogenous properties have led to the understanding of wood as a generic material to achieve shape. This shift also had broader implications for the creative domain of artists and craftsmen and professional designers such as architects. As Hentie Louw put it, "The machine … had now also begun to impinge seriously on the creative domain of the artist and craftsman, and to undermine the position of professional designers like architects" (Schindler 2009: p. 157).

However, tacit knowledge rooted in crafts has fueled innovations in technology and design. It has been passed down through generations of carpenters and can now be re- interpreted digitally (Menges *et al.* 2016). Computational design and manufacturing tools enable the integration of material-, construction-, and fabrication-specific parameters into design and construction (Kolarevic & Klinger 2013). Thus, they enable the processing of heterogeneous materials with anisotropic properties, empowering designers to utilize the material properties of timber during the design process (Allner & Kroehnert 2019). Paradoxically, while today's building industry embraces highly advanced levels of technology, construction practices and technical solutions have not changed significantly for many centuries.

1.3 *The Dimensional Change of Timber*

Timber is a moisture-responsive material that swells and shrinks with changes in the humidity. Wood's dimensional change (DC) to atmospheric conditions is a key biological characteristic of vascular tissues (Correa *et al.* 2019). Managing the DC is important for timber construction. Excessive changes in the moisture content can lead to dimensional changes in the wood, causing warping, twisting, and splitting. This can compromise the structural integrity of buildings. In addition, high moisture levels in timber can encourage the growth of mold and rot, which can weaken the wood and potentially cause health problems for

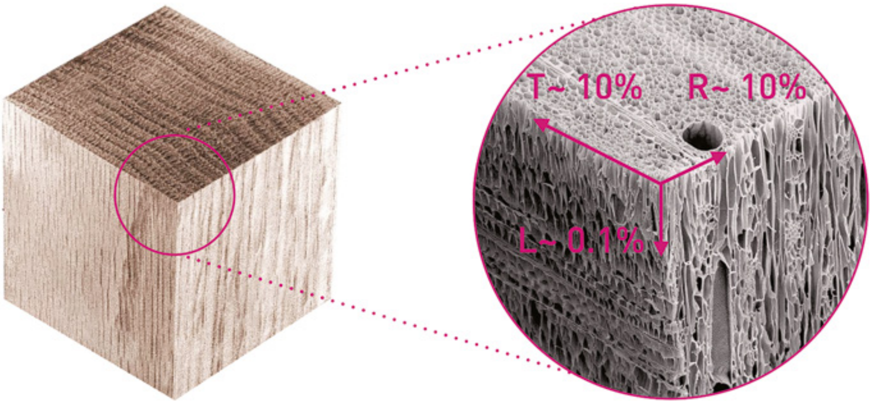


FIGURE 1 Macro (left)- and microstructure (right) of wood, showing fiber direction and orientation of cells responsible for moisture transportation and dimensional change of timber in relation to fiber direction, values in tangential (T), radial (R) and longitudal (L) direction from 0 to approx. 30% moisture content (own illustration)

occupants. Additionally, the moisture content affects the strength and stiffness of wood, making it important to ensure that the wood is not too dry or wet. Therefore, it is essential to control the moisture content of timber elements to ensure structures' long-term durability and safety (Mjörnell & Olsson 2019).

The percentage of dimensional change (DC) varies depending on the fiber orientation, with swelling or shrinking being the highest in the tangential direction (Fig. 1). As the timber dries, it sheds water from the cells and fiber walls. First, the bound water in the cell walls is shed; under approximately 30% moisture content (MC), free water is shed, causing contraction and changes in dimensions. However, wood's natural shape memory effect means that it can return to its original shape after cyclic moisture changes, making it a smart material (Ugolev 2013).

Structural timber has varying MC values, depending on its design and atmospheric conditions. Standard values for timber in use range from 6–22%, depending on the location of the elements and construction type (Kolb 2008). Eurocode Standards establish precise values for calculating deformations under specified environmental circumstances (Ramage *et al.* 2017). Woodworkers can create objects that can adapt to different environmental conditions by designing joints that accommodate these changes. This adaptability is crucial in diverse climates and locations where wood is exposed to varying moisture and temperature levels throughout the year. Wood joints that do not account for the natural movement of wood may cause damage such as warping, splitting, or cracking. Woodworkers minimize the risk of damage by utilizing joints

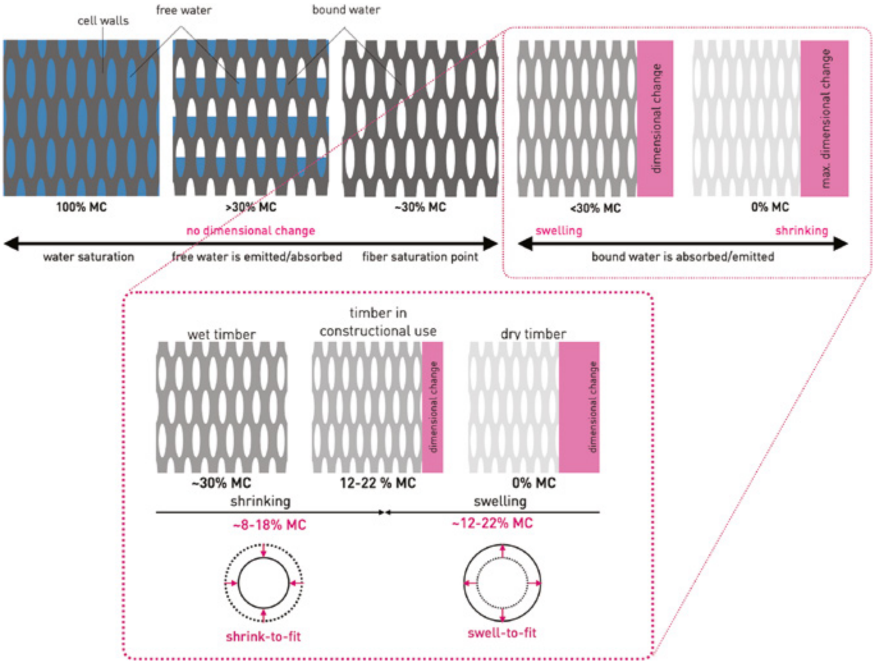


FIGURE 2 Hygroscopic behavior of timber, ratios of dimensional change for timber in constructional use due to variations in moisture content and diagrammatic description of the two principles utilizing dimensional change for joining (own illustration)

that allow for swelling and shrinking. This is particularly significant in large-scale construction, where the cumulative effects of dimensional changes can lead to severe structural issues. However, rather than simply accommodating this material characteristic, woodworkers also utilize either shrinking or swelling of the material to join the elements. These methods can be defined by two distinct principles: “shrink-to-fit” and “swell-to-fit” (Fig. 2).

Artisans have long used joining techniques that take advantage of the dimensional changes in timber (Zwerger 2015). Swelling dowels, a sustainable and bio-based alternative to adhesives and metal fasteners, have been used in engineered wooden products, such as dowel-laminated timber, since the 1970s (van der Lugt & Harsta 2020). These connections reduce the embodied carbon (Fang 2020), improve re-use or end-of-life disposal (Mehra *et al.* 2018), and are less prone to failure from fire and corrosion compared to steel fasteners (Anagnostou 2018; Thomson *et al.* 2010; Wojcik 2020). Thus, mono-material timber connections are more beneficial for the longevity and sustainability of structures than the steel elements commonly used in timber joints (Jeska 2014). Furthermore, owing to the high pressures generated by swelling, joints can achieve a reliable form-and-friction fit (Thoma *et al.* 2019). Thus, the structural capacities of the joints can be manipulated. Increased friction between elements can reduce the need for additional fasteners while maintaining the structural capability owing to the better transfer of forces within the joint itself.

1.4 *Technological Advances in Timber Construction*

The timber industry has quickly adapted new technologies from harvesting to manufacturing and assembly (Wu & Kilian 2019). This significantly influences the interaction with the material. Two trends in timber technology are observed: material integration and material modification. Material modification mainly utilizes the material properties of the components or engineered wood products. Technological progress has made it easier to break up the natural log into the required parts and reorganize its substance into new wood-based products (Menges 2016). For instance, *Accoya* is created through acetylation, which involves the chemical modification of wood to improve its performance and durability. It is treated with acetic anhydride, which reacts with the wood's natural components to produce acetylated wood, changing the wood's cell structure and making it more stable and less susceptible to swelling, shrinking, or warping due to moisture changes (Lankveld *et al.* 2015).

Material integration seeks to understand material properties as generative parameters for the design (Allner & Kroehnert 2019). It explores the use of timber as a natural, low-engineered material and aims to integrate the tree's anatomy and its heterogeneous properties into the constructional logic of structures (Menges *et al.* 2016). Architects and engineers can consider the manufacturing and assembly parameters early in the design process (Sass *et al.* 2006). These two trends influence the design space and roles of designers. Material modification allows for greater formalistic design freedom, whereas materials play a decisive role in the design process of material integration. Designers seek to balance formalistic design requirements, material-based construction principles, and details. Digital technologies can change architectural design and the building industry (Correa *et al.* 2019). Therefore, architectural design research focuses on how to use materials, taking advantage of technology's evolution (Naboni 2017) rather than the material to use.

1.5 *Problem Statement*

Wood culture can be defined as the accumulated knowledge of wood use throughout human history. This study encompasses traditional craftsmanship, architectural design, construction, and industrial production. It extends beyond recorded history and is one of humans' oldest construction methods. It has continuously evolved with technological advances; however, standardization and fragmented processes in industrialization have led to a loss of understanding of wood`s heterogenous properties (Shanks *et al.* 2014). Consequently, anisotropic materials are no longer designed (DeLanda 2004). The ability to customize wood performance through material engineering and fabrication is one of the reasons for its significant potential in the 21st century (Correa *et al.* 2019). However, a material′s ability to respond to the environment is often viewed negatively, and measures are taken to neutralize it (Hensel 2009). The timber industry limits or controls dimensional changes to satisfy stringent building codes and regulations. However, these forces have rarely been integrated into design and construction applications (Correa *et al.* 2019).

Dimensional changes have gained research interest, with shape-changing elements introduced in prototypical applications, such as the Hygroskin Pavilion, full-scale architecture projects like the Urbach Tower (Wood *et al.* 2020) and product design (AlHajri, 2022). These projects demonstrate the potential of utilizing this complex material behavior. However, the use of DC for joining elements remains limited to contemporary building practices. Swelling dowels are primarily used in EWP production (Mehra *et al.* 2018) (Sotayo *et al.* 2020), whereas shrinkage is rarely used in industrial building processes (Mougel *et al.* 2011).

A multidisciplinary approach combining materials science, manufacturing technology, and architecture is necessary to develop new value-added timber products and high-performance applications. Existing principles, techniques, and technologies are often only known to specialized professionals in separate fields. However, the relationships among existing techniques, connection types, building elements, technological advancements, and their potential for building construction and wood culture have not been investigated in a broader context.

1.6 *Research Objective and Question*

This study evaluated the state-of-the-art utilization of the DC of timber to join timber elements in building construction. It documents techniques used in crafts and industrial buildings, outlines the influence of crafts on modern applications, interdependencies between existing techniques, architectural applications in contemporary building practice, and technological advancements in industry and research, and reflects on the role of these techniques and developments in wood culture. By encouraging future research, technological innovations, and design opportunities in the field, this study aims to support the use of DC for joining timber in contemporary building practices.

- What is the state-of-the-art approach for utilizing the dimensional change of timber to join timber elements in building construction?

The following sub-questions specify the formulation of the main question:

- Which techniques enable the utilization of the DC for joining timber elements?
- Which principles and technological approaches do these techniques follow?
- Which connection types and building elements can these techniques be applied to?
- What is the influence of crafts on these techniques?
- What potential constraints and research gaps can be identified regarding implementing these techniques in contemporary building practices?
- What potentials do digital technologies herald for these techniques?
- What role does the utilization of dimensional changes in joining play in wood culture?

2 Materials and Methods

The study is based on a systematic literature review, divided into three steps: building a body of literature, identifying individual results, and mapping the interdependencies of the results.

2.1 *Building a Body of Literature*

First, a body of literature was constructed and further expanded during the research process. The initial body of literature was generated through a filtered search in Scopus (Table 1).

The following steps were taken to create the body of literature. Steps B-F were repeated in iterations:

A. scan academic databases
B. scan abstracts
C. select relevant literature
D. scan references
E. select additional relevant literature
F. scan literature

2.2 *Identification of Individual Results*

This study focused on techniques for using DC in joining. Techniques were identified, classified according to their principles, and evaluated for their potential and constraints. Subsequently, the connection types and building elements to

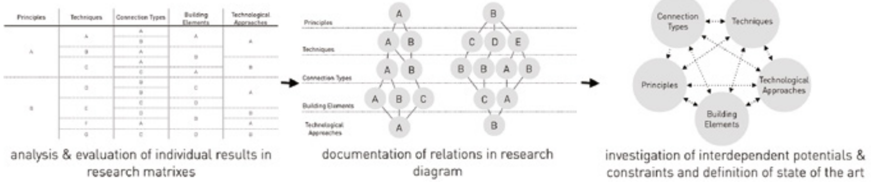
TABLE 1 Search and filtering parameters for SCOPUS (own illustration)

Description	Parameter
Search terms	(Wild card * indicates the term includes variations on the word such as plural/ singular and noun/adjective)
First term in search string	wood; timber
Second term in search string	join*; connect*; dowel*
Third term in search string	swell*; shrink*; dimension*; hygroscop*
Exemplary search string	(TITLE-ABS-KEY (wood) OR TITLE-ABS-KEY (timber) AND TITLE-ABS-KEY (_join*_) OR TITLE-ABS-KEY (_connect*_) OR TITLE-ABS-KEY (_dowel*_) AND TITLE-ABS-KEY (_hygroscop*_) OR TITLE-ABS-KEY (_swell*_) OR TITLE-ABS-KEY (_shrink*_) OR TITLE-ABS-KEY (_dimension*_))

which these techniques are applied are defined and documented in a research matrix, along with references. Finally, the potential and constraints of the individual results were investigated in the context of the utilization techniques.

2.3 *Mapping Relations of Results*

A research diagram was used to map the relationships between individual results. The diagram is based on the research matrix and maps individual techniques to utilization principles, connection types, building elements, and technological trends in timber technology. This helps to define potentials, constraints, and research gaps in these areas and evaluates the state-of-the-art in utilizing dimensional changes to join timber elements (Fig. 3).



analysis & evaluation of individual results in research matrixes

documentation of relations in research diagram

investigation of interdependent potentials & constraints and definition of state of the art

FIGURE 3 Schematic research process, from evaluation of individual results in research matrixes to documentation of results in research diagram to investigation of interdependent potential and constraints to define of state-of-the-art (own illustration)

3 Results

3.1 *Techniques in Utilizing the DC: Shrink-to-Fit Techniques*

Underscribing, drawing, and manufacturing of special joint geometries utilizing the shrink-to-fit method were developed by craftspersons, skilled or non-skilled, using green timber as a construction material. Other joining methods often require much harder sources and more processed materials and thus require energy- and cost-intensive materials, such as ropes or metal fasteners. Artisans had to accommodate dimensional changes in freshly felled timber to avoid long drying times. Moreover, green timber is much softer and easier to process (Alexander 1978), so these techniques allow further energy and time savings during construction. These green woodworking techniques were developed in peasant communities and are usually based on local needs, trading, and minimal involvement with the official economy. Here, woodworking was often a task for the winter, when there was slack in farm work, and was often carried out by non-specialized persons. Knowledge was passed down orally from generation to generation by imitating and learning these techniques. After a decline in crafts due to industrialization and the specialization of craftspeople, green woodworking has regained popularity for the products created and the craft itself. These techniques are still applied, and the craft is evolving, with new designs for furniture and new inquiries by craftspeople into the further development of techniques, such as the design guidelines for greenwood joints by John Alexander (Langsner 1987).

3.1.1 Underscribing

Underscribing is a log-building technique developed in 1982 by Del Radomske, a loghome builder in British Columbia. He noticed that the grooves in his buildings remained tight, whereas most of the corner notches became loose when changing from a green to a dry state, owing to the varying radial shrinkage on the logs (Fig. 4). Before Radomske, the logs were scribed using one scribe setting. During underscribing, the notches and grooves were scribed using slightly different scribing settings. It is common to use one scribe setting for the groove and a slightly different setting for the same log notches (Fig. 5), resulting in significantly tighter corner notches over time. The notches were cut, leaving additional material as they shrank. The amount of underscribing depends on the moisture content and log diameter. It is essential to prevent joint failure owing to shrinkage and the resulting crushing of the cells in the joint. Precise values rely on the experience of the craft person, and some formulas have been documented in the literature. Log cabins are still common in Scandinavian

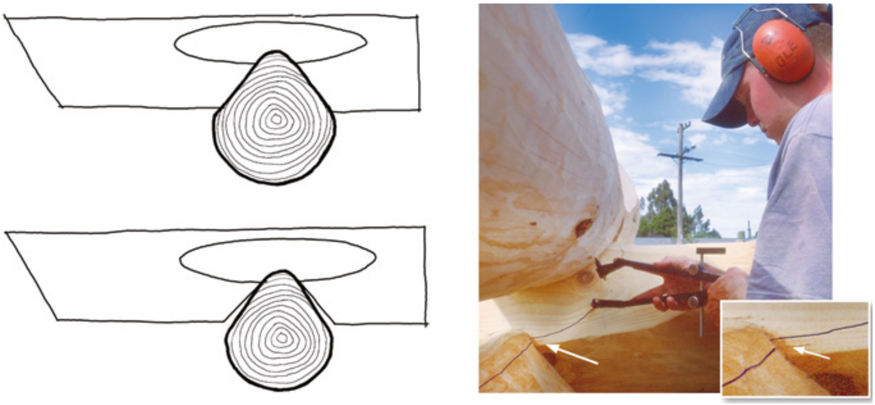


FIGURE 4 Details explaining underscribing. (Left) loose notches on saddle due to radial shrinkage of logs from green (top) to dry (bottom) state (own illustration after (Chambers 2006)). (Right) The process of underscribing a log house, first the grooves are scribed, then he scribers are closed slightly and then the notches are scribed (Chambers 2006)

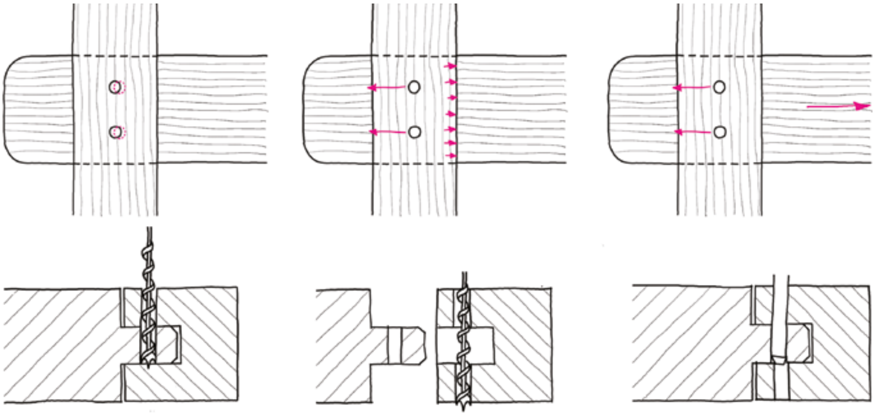


FIGURE 5 Drawboring, principle and process. (Top) diagram explaining the principles of drawboring, from left to right; borings offset from mortise to tenon, prestress in joint, joint loaded in tension (own illustration after Sobon & DeStefano 2020). (Bottom) Manufacturing sequence of a drawbored joint, from left to right; predrilling angled boring half of the mortise and tenon in semi-assembled state, boring the second half of mortise in right angle, using tapered peg to draw joint tight

countries (Ilgin & Karjalainen 2022), Canada, and the US, and description is still commonly applied. This technique is labor-intensive and requires specialized tools but is not cost-intensive. This has not changed much; although machines are used to cut grooves, the process is still manual and craft-based (Chambers 2006).

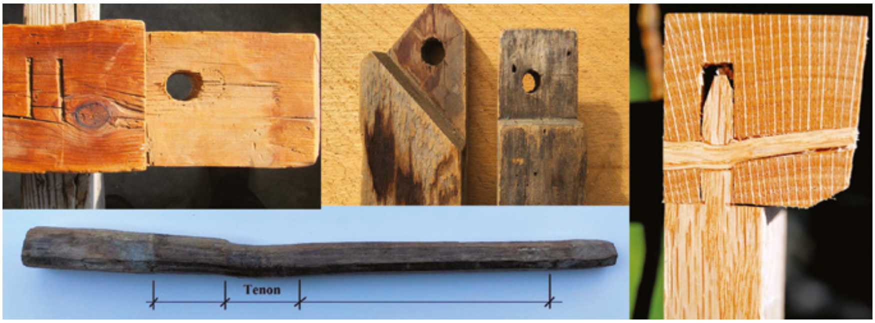



FIGURE 6 Examples of drawbored joints. (Top right) The peg holes location is pricked onto the tenon on a Dutch barn frame from 1801 made out of eastern white pine; (top middle) Clearly visible layout markings on these two tenons, left in red Red Spruce from around 1855, right in a Sugar Maple rafter from around 1820 (top right) Cut through a drawbored joint in oak, clearly visible deformation of pin drawing the mortise into the tenon (Lost Art Press 2021); all others (Sobon & DeStefano 2020)

3.1.2 Drawboring

Drawboring dates back to the 13th century and was revived in England in the 1970s (Ross *et al.* 2007). This is sometimes referred to as "pull-boring" or "draw-pinning," and is a technique developed for greenwood timber framing to ensure tight-fitting joints during shrinkage. To manufacture a mortise and tenon joint connecting two members subjected to tension, this method uses pegs to pre-tension the joint (Fig. 6). The pegs (historically called pins, tree nails, or trunnels) were traditionally split from straight-grained hardwood, including Northern Red Oak (*Quercus rubra*), White Ash (*Fraxinus americana*), and hickory (*Carya*). In contrast, rot-resistant species, such as White Oak (*Quercus alba*), Black Locust (*Robinia pseudoacacia*), and Black Cherry (*Prunus serotina*), were preferred for damp or rot-prone areas (Fig. 7). The pegs were carefully chosen to be structurally perfect without knots, cross grains, wanes, shakes, decays, or other defects that weaken the wood. Billets for the pegs were cut from clear sections of the lower trunk, preferably from non-leaning trees, to avoid wood tension and facilitate the cleaving process (Sobon & DeStefano, 2020).

There are several variations of this technique. In the first, the location is "eyeballed," the hole is bored in the mortise first, and the drillhole is then used to prick the peg's location on the tenon using a scratch awl, gouge or auger bit. This mark is visible in the joint of a Dutch barn frame from 1801 (Fig. 6). The tenon was removed, and the remainder of the hole was drilled on the other side. An offset between the mortise and tenon boring was achieved by not bringing the joint to a bearing during pricking. The variation was used to angle the boring in the tenon towards the shoulder of the joint, providing an inclined plane

FIGURE 7 Examples of shrink-fit-joints. (Left) The "shrink-to-fit" notch, or Beckedorf Butterfly joint on a log home from Lloyd Beckedorf of Moose Mountain Log Homes (Chambers 2006). (Middle) Shaker rocker chair joined by shrink-to-fit tenon-and-mortise joints ((Alexander 1978). (Right) Details to enhance friction-fit of greenwood shrink-to-fit mortise-and-tenon joints (Alexander 1978)

that pulled the joint together (Sobon & DeStefano 2020). (Schadwinkel *et al.* 1986) described a variation in which the first hole was drilled in an assembled state with a small gap between the mortise and tenon elements. It was angled and penetrated the first halves of the mortise and tenon. The joint was then disassembled, and the remainder of the boring was drilled at a right angle, choosing an offset such that the tapered end of the peg met the boring (Fig. 5).

After 1800 square rule framing emerged, and joints did not have to be scribed but could be laid out and manufactured separately. The offset between the mortise and tenon bringing was laid out using a framer's square and marked on both joining features (Fig. 6) using established measurement design guidelines. For example, the tenon length should always be at least twice its thickness to enable pinning. The borings were drilled at right angles, and the offset between them was used to pull the joint tightness. On some English tying joints, the top tenon securing the tie beam was offset in two directions, vertically to the shoulder and horizontally, to anticipate the shrinkage of the post and prevent splitting. On exceptionally deep members that exhibit greater width shrinkage, holes are offset towards the bottom and weight-bearing side of the tenon. These variations create tight-fitting joints, eliminating the need for assembly aids during the erection and assembly of the frames (Sobon & DeStefano 2020).

3.1.3 Shrink-Fit Joints

Shrink-fit joints are another technique applied when joining logs. Generally referred to as saddle notches, various joint geometries, such as the Scandinavian or compression-fit saddle notch, have been used to join the corners of log houses. However, these joints highlight the necessity of ensuring tight joints during log shrinkage. Artisans have adapted the geometries of existing joints with beveled surfaces to anticipate varying radial shrinkage and thus prevent gaps during shrinkage (Zwerger 2015). The most effective notch, the Beckedorf or butterfly notch, was developed by Lloyd Beckedorf (Fig. 9). Here, instead of being flat or slightly concave, the saddle is convex, meaning it is higher at the center. However, (Chambers 2006) found that these generally work better on larger log diameters, as they increase the saddle's center farther than on small-diameter logs. Construction companies have developed various geometries for industrial manufacturing. These joint types are still used today, especially in the northern USA, Canada, and Scandinavian countries where log cabin construction is common. The Scandinavian notch is primarily used in Norway, Finland and Russia.

Shrink-fit joints are also used for making greenwood furniture (Langsner 1987) (Fig. 7), with elements shaped according to the fiber orientation to optimize the strength. The material characteristics were assessed by eye and sound, and the zones of maximum shrinkage were oriented in the plane of maximum stress.

The mortise and tenon connections have slightly over-dimensioned bearing surfaces (by approximately 1%) and slightly undersized non-bearing surfaces to account for the varying shrinkage. To ensure tight-fitting of the tenons, they were usually dried to 5–8% before fitting the joints to ensure their minimum dimensions were considered in the dimensioning joints. The ideal moisture content for mortises is approximately 15–20%, allowing for slight swelling of the tenon owing to moisture exchange with the mortise. The joint's true strength results from shrinking the mortise (Zwerger 2015). Additional geometric features such as flattened tenon sides and dovetailing enhance the interlocking and pull-out strengths. Notches on the top and bottom of the mortise increase the interlocking and pull-out resistance (Alexander 1978) (Fig. 7).

Renbutsu & Koizumi (2018) investigated the clamping pressure in greenwood joints to enable the full capacity of adhesives. The green mortise and tenon joints were assembled using a polyvinyl acetate emulsion. A comparison with regular joints, where epoxy was used to ensure the adhesion of elements, showed comparable results regarding pullout strength, which did not significantly decrease after exposure to four humidity cycles.

Wojcik (2020) investigated the use of the shrink-to-fit principle with specialized joint geometries and its potential to reduce adhesives and metal connectors, which are often used to manufacture wooden building components. In this study, the principle of Interlocking Cross-laminated Timber (ICLT) is investigated; however, instead of utilizing dovetail geometries to join lamellas,

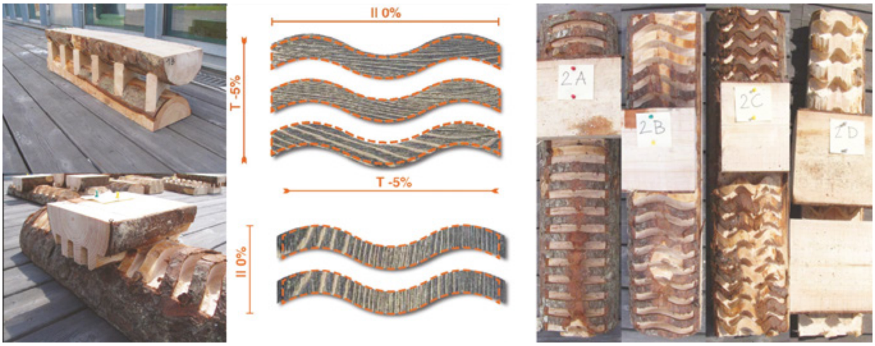


FIGURE 8 Experiments in utilizing shrinking for joining. (Left) Two experimental prototypes, (top) “Dry-in-wet”, using external inserts to connect elements. (bottom) “Wet-in-wet”, with milled incisions to connect logs. (middle) Tangential (T) and longitudinal (II) shrinkage as connection mechanism (orange lines indicate sizes after shrinking). (Right) Testing of various incision geometries for the WIW-prototype. All illustrations by Wojcik (2020)

a dimensional change is utilized to create friction-fit connections for prototypical internal and external wall components. They used halved wet logs as active shrinking agents to create biodegradable wall panels. Two joint configurations were investigated, namely “dry-in-wet” and “wet-in-wet” (Fig. 8). In the dry-in-wet method, external but inactive connector elements were used, with incisions cut into them while wet to create a friction-fit connection upon drying with external pine elements. Various configurations of the geometry, distribution, and dimensions of the incisions and inserts were studied (Fig. 8). In wet-in-wet, two wet elements are joined without connectors to create a dense wall element. At the structural level, the capability of shrink-to-fit mortise and tenon joints was found to increase considerably compared with conventionally joined samples (Mougel *et al.* 2011).

3.2 *Techniques in Utilizing the DC: Swell-to-Fit Techniques*

The drying, compression, and densification techniques, which utilize the swell-to-fit principle, follow the opposite approach. Swelling is used to create tight-fitting connections.

3.2.1 Drying

Drying is the most basic and oldest technique for enhancing swelling behavior. Swell-to-fit techniques, such as compression and densification, are often combined with drying to amplify swelling. The most common technique is the use of pre-dried swelled dowels. Artisans often used homemade kilns (Langsner

FIGURE 9 Craft based drying methods. (Left) Drying of wooden elements in home-made kiln. (Right) Local drying of tenon on chair rungs in hot sand. All illustrations by Langsner (1987)

1987) (Fig. 9) to dry them with heat. In industry, large-scale convective kiln drying is used (Pereira *et al.* 2021), along with other methods, such as drying in silica gel. Tenons in greenwood chairs were dried for furniture production before insertion into wet mortises. Here, the local drying of features is achieved by drying tenons in hot sand (Fig. 9) or by using aluminum foil to shield areas (Langsner 1987). Silica gel can also be used here (Covington 2020).

Pre-dried dowels or joining features are inserted into the joinery elements to induce swelling and ensure they remain in place. Usually, they are conditioned to a low MC of around 6–8% and inserted into predrilled holes in elements with a higher MC. The RH in the ambient air reconditions the dowel and induces swelling (Fig. 10). This principle has been used in a range of applications, including farming utensils such as rakes (Fig. 11), furniture, and timber structures.

Mateo Timber Peg is a direct adaptation of this technique, transferring it from craft to industrial production. They were manufactured from previously dried beech or ash wood and vacuum-sealed to prevent unintended swelling. They settle at an equilibrium of approximately 7–8% MC (depending on the MC of the elements they are installed). It can join elements of various joint geometries and materials, such as mass timber and cross-laminated timber (CLT) (Knapp Connectors n.d.). Custom-designed swelling connectors from beech are also used in large-scale commercial buildings, such as Tamedia HQ (van der Lugt & Harsta 2020) and Bjergsted Finance Park (Rando 2019) (Fig. 12).

A widespread industrial application of this technique is in producing engineered wooden products, mainly timber plates, further developing the

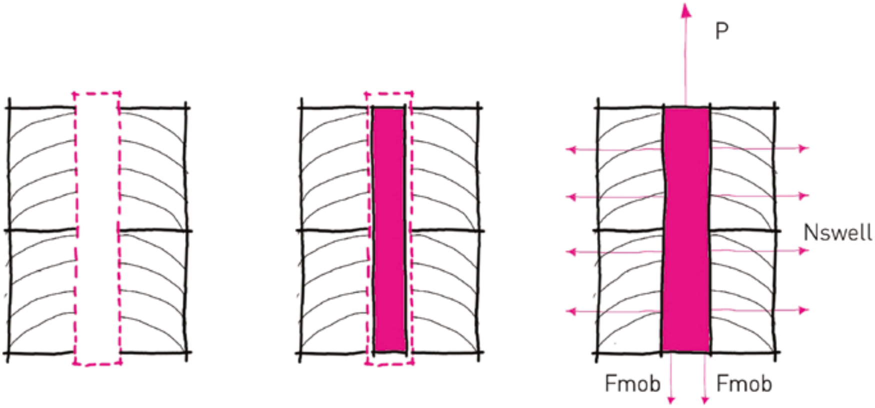


FIGURE 10 Diagram of moisture-induced friction-locking of swelling dowels. (Left) Pre-drilled hole; (middle) dowel insertion; (right) dowel swelling and creating a frictional resistance force (F_{mob}) between dowel and element when dowel is subjected to pullout force (P) (own illustration after Lei *et al.* 2023)

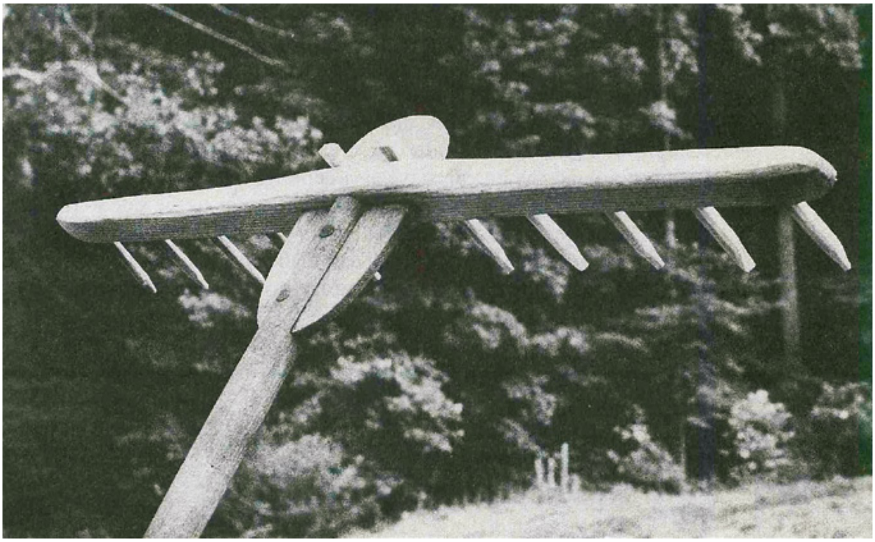


FIGURE 11 Swelling pins used in a rake based on a traditional finish design, the pins attaching the head to the handle via a disk are drawbored (Langsner 1987)

concept of *Brettstapel* panels but replacing steel nails with swelling dowels to create mono-material timber elements (Sotayo *et al.* 2020). This technique also allows using structurally low-grade timber that would otherwise be unsuitable for construction. Various systems are available, such as StructureCraft dowel-laminated timber (DLT), in which lamellas are joined edge by edge via

FIGURE 12 Pre-dried dowels. (Left) Mateo Timber peg (Knapp GmbH). (Right) Custom beech dowels utilized in the Bjergsted Finace Park (Sindre Ellingsen)

pre-dried hardwood dowels. A wide variety of systems and panel layups are available and can be customized to meet the needs of the designers. The manufacturing process allows the production of large spans, and the size of the panels is limited only by transportation (StructureCraft, 2019).

DCLT uses swelling dowels to join directionally alternating layers via a perpendicular assembly. The Thoma System Holz100 was motivated by creating monomaterial timber houses inspired by solid timber log buildings. In addition to the alternating perpendicular layers, layers were also oriented at 45°, structurally taking on the role of bracing elements traditionally found in post- and beam timber structures (Fig. 13).

For joining, beech dowels dried to 2–4% before insertion and reached an EMC of 12–15% after swelling was used. This product is available in thicknesses and layer variations, enabling a wide range of applications (Fig. 13).

The Rombach Nur-Holz DCLT also uses beech dowels that are threaded and screwed into the lamellae (Fig. 13). The dowels were dried to 8%–10% MC, and the fir lamellae had an MC of 10–12%. The system can also be ordered as ready-made components and adapted to building designs, with window cutouts and routing for installations already integrated into factory elements (Rombach Bauholz + Abbund, 2019). These developments have significantly influenced timber construction, as new EWP have expanded construction possibilities and facilitated new timber construction systems (van der Lugt & Harsta, 2020).

New applications and the potential of pre-dried dowels are also examined in academic research projects, investigating the design space for using dowels to join elements on-site. ETH Zürich researchers developed a layer-based construction and robotic fabrication method for bespoke wood-only assemblies

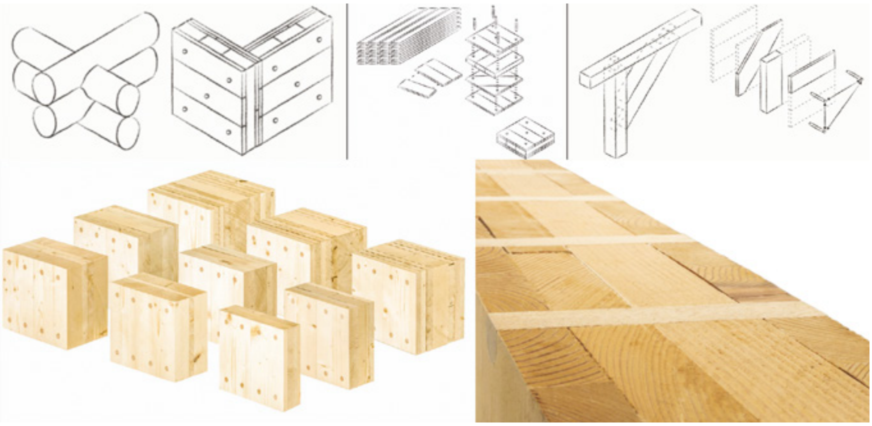


FIGURE 13 Concept and Assortment of Rombach Holz100 DCLT (Rombach Bauholz + Abbund). (Top) (left) Solid timber log construction as antetype for DCLT; (middle) setup of layers at 0, 45 and 90° orientation; (right) traditional carpentry bracing as antetype for 45° layer. (Bottom) (left) Assortment of Holz100 DCLT variations; (right) section detail of swelling dowel. (Thoma Holz)

using swelling dowels, thereby expanding the design space of DLT from planar to curved geometries. The assemblies consisted of layers of spruce slats connected by beech dowels locked in place through a tight-fit friction joint. The beech dowels were oven-dried to shrink and then sprayed with water to expand them for a tight-fit connection (Thoma *et al.*, 2019). This system was used in the "Gradual Assemblies" Pavilion. Two research prototypes at the University of Waterloo used the hygroscopic expansion of wooden dowels to lock the bent plywood sheets in place. Moisture-activated dowels self-align and fasten components, reducing the need for metal fasteners. Hardwood dowels expand and lock connections as they absorb moisture, thus ensuring a rigid and permanent connection. The diameter and moisture content of the dowels were checked and equalized prior to fabrication and then reduced to 4–6% equilibrium moisture content (EMC) in a climate-controlled chamber, resulting in a 5–10% change in diameter (Correa *et al.* 2019).

The development of components is also being investigated, (Schmidt-Kleespies, 2020) developed Interlocking Dowel Systems (IDS) for load-bearing wall-segments using swelling dowels. Two coplanar LVL sheets were joined by dowels inserted at skew-whiff angles, allowing custom load-optimized wall segments. Using load-specific dowel patterns allows for the easy retrospective adjustment of existing wall openings without a detailed redesign, opening up a new approach to designing the outer skin of timber frame structures. Using pegs with alternating skew — whiff angles is related to the traditional joining

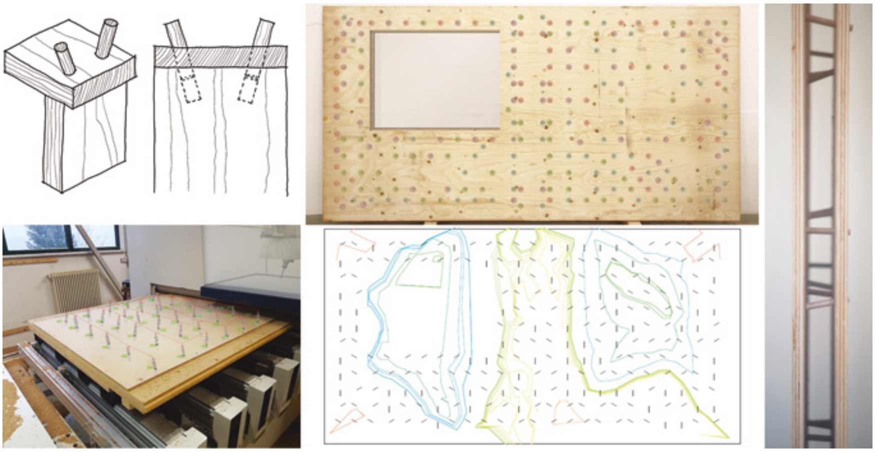


FIGURE 14 (Top left) Alternating dowels as ante typical joining method for IDS system. (Bottom left) Manufacturing of IDS panels via a 5-axis CNC mill. (Top right) IDS prototype with dowels marked and force field lines in a simulation of a unilaterally fixed wall element with window opening. (Bottom right) Side view detail of wall element with alternating dowel angles visible. (Top left) Own illustration after Spannagel (2020), all others Schmidt-Kleespies (2020)

method of inserting wooden dowels at alternating angles in furniture and utensil-making (Spannagel, 2020) (Fig. 14).

However, investigating the structural capacity of swelling dowels, (Groenquist *et al.* 2018) and (Lei *et al.* 2023) found that a continuous decrease in relative humidity over time can lead to nonlinear creep under a mechanical load and thus to complete loss of contact pressure between connected elements, potentially leading to connection failure.

Drying is not limited to external connectors but applies to integrated joineries. Japanese carpenters kiln-dry lumber and reduce the moisture content to less than ten percent before cutting the joints. The joining features are then cut into sizes. After joining, the members swelled and formed tight-fitting joints without tolerance. The elements were dried as a whole and immediately assembled after exposure to moisture (Amino 2004). This technique is still used in Japan today (Zwerger 2015). However, precise documentation of these techniques cannot be found in the literature.

Information on local or global manipulations or measures to integrate the swelling of entire building elements into the design of connections or structures is sparsely documented. Further research can provide valuable insights into advanced material modification techniques and design principles. The larger size of building elements and features in timber construction makes upscaling techniques commonly used on a furniture scale necessary and could present a threshold in the utilization of swell-to-fit techniques in integrated joinery. The results of (Mougel *et al.*, 2011) indicated that the structural capability of shrink-to-fit mortise and tenon joints increases considerably compared to conventionally joined samples.

3.2.2 Compression

Mechanical compression is another technique used to enhance the swelling behavior of wood. Form and friction fit is created by crafting elements with an oversized fit and compressing the material before joining. Termed *kigoroshi* means "killing the wood," here, wood is mechanically compressed by hammer strikes (Satō & Nakahara 1995). The fibers swelled back into the original decompressed state by wetting the material. It is used on integrated male joinery features, such as tenons or external connectors, to form a tight fit between elements. It only works on long grains and requires experience because its manual application in the direction and amount of compression is crucial to prevent fiber cutting and decompression failure (Moriyama 2015; Covington 2020). This technique has also been used to tighten joints and prevent water entry in boatbuildings and bridges, where the sides of the planks are compressed prior to joining. The sides gradually decompress when joined, forming tight seams between the boards (Moriyama *et al.* 2015).

This technique was adapted using compression combined with drying for furniture connectors with various joint types and geometries. He described and patented oversized compressed dowels in various joint types and geometries, including integrated joineries, dovetails, and freeform connectors (Berthold 1993).

Mechanical compression has also been applied to the production of engineered wood products such as Holz100 (Thoma Holz 2018) and NurHolz (Rombach Bauholz + Abbund 2019) dowel cross-laminated timber (DCLT). The Holz100 system compresses dowels in addition to drying them. They were compressed from 22 mm to 20 mm in diameter, inserted into 20 mm borings, and corrugated transverse to the insertion direction to enhance the friction fit. The NurHolz system utilizes swelling due to drying and enhances this effect by threading dowels and compressing the female joining feature. These opposing threads in the lamellae are not cut but compressed into the material; thus, both the dowel and opposing threads can swell, leading to an increased form and friction fit (Fig. 15). The use of screws in wood culture is deeply engrained. Its use until about 1000 or 2000 BC in Pompeii, a wooden press used for flattening clothes from 79 AD, exhibits wooden screws in great condition (Landis 1991). A range of woodworking tools, such as clamps, workbenches, and adaptable planes, incorporate screws as essential functional elements (Schadwinkel *et al.*

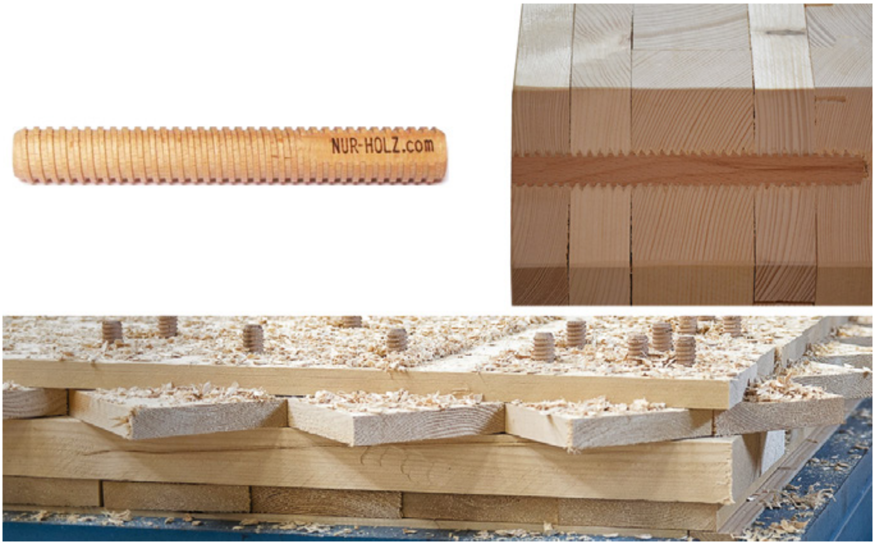


FIGURE 15 (Top left) Threaded beech dowels used in the NurHolz system. (Top right) Cut section of a NurHolz panel showing form- and friction fit of the dowels in the lamellae. (Bottom) DCLT panel production with alternating layer setup and screwed in dowels. All illustrations by ROMBACH Bauholz + Abbund

1986). This is similar to the concept of using decompression to form tight seals between boards with external connectors (Moriyama *et al.* 2015) can be drawn.

3.2.3 Densification

The terms used in the literature for the densification techniques differ. The most common term is densification, which will be used in this research. This involved heating and compressing the timber perpendicularly to the grain. Timber mainly consists of fibers and lignin. Heating it beyond the glass temperature of lignin (ca. 130°C) allows deformation of cell walls. This deformation changes the swelling behavior of timber. A phenomenon called 'shape memory' is present in densified timber. It exhibits reversible swelling due to hygroscopicity and irreversible swelling due to densification (Laine *et al.* 2013). Densified timber tends to recover from compression as soon as it is exposed to moisture and recovers close to its original state when soaked in water (Cabral *et al.* 2022) because of spring-back (SB) and set-recovery (SR). SB is defined as the thickness recovery of densified wood immediately after the compression load is released, due to lignin's thermoplastic nature. SR is also a thickness recovery but occurs after the replasticization of the densified timber during usage (Cabral *et al.* 2022) (Fig. 16).

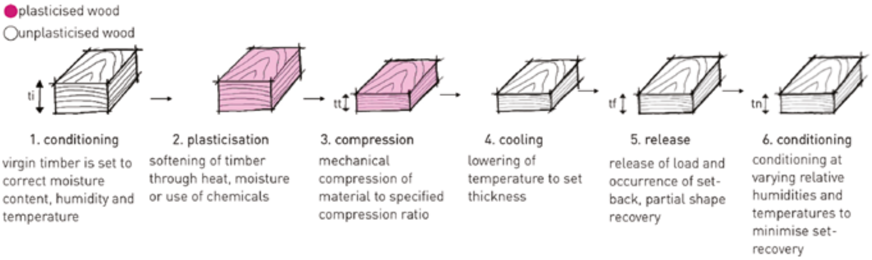


FIGURE 16 Schematic description of different stages of densification process and material dimensions, from initial thickness (t_i) before conditioning to target thickness (t_t) during compression, to final thickness after release from press (t_f) to thickness during use and replasticisation (t_n) own illustration after Cabral *et al.* (2022)

This swelling behavior depends on factors such as the wood species and process parameters. Several modification processes exist, motivated by further ensuring the dimensional stability of dW. In thermomechanical densification using only heat and pressure, the SB and SR and thus the swelling, are the most pronounced. Thermo-hydro-mechanical densification, in which the material is stabilized through steam injection before or during the compression stage, improves the dimensional stability of timber owing to steam softening of the lignin and hemicellulose matrix. Other methods involve adding chemicals or resins to suppress the shape-memory effect (Cabral *et al.* 2022). Densified wood exhibits higher swelling ratios, faster swelling times, and more persistent swelling pressures than natural wood (Anshari *et al.* 2011). Swelling was more pronounced, with natural samples swelling by approximately 5%, whereas densified samples swelled by up to 85%. Regarding the duration of swelling, natural samples reached almost maximum swelling during the first 30 s, while densified samples continued to swell for over 3.5 h and more (Laine *et al.* 2013). Mehra *et al.* (2021) compared the swelling ratios of nW and dW dowels over several cycles of moisture change. As a result, they provided a much higher pull-out strength (up to 387%) than conventional swelling dowels (Fig. 17).

Swelling dowels were used to join laminated timber as an adhesive-free Glu-Lam alternative beam, and the moisture-induced swelling and SB of the dowels were used to ensure a tight fit (Mehra *et al.* 2020). El-Houjeyri *et al.* (2019) characterized the use of densified wood dowels in adhesive-free laminated timber beams and found that the mechanical performance of compressed wood in three-point bending tests was improved by a factor of two compared with that of natural wood. The use of dW as a dowel in friction-locked joints is a solution to overcome long-term performance problems such as wood viscoelasticity-induced strength loss, stress relaxation, and creep deformation,

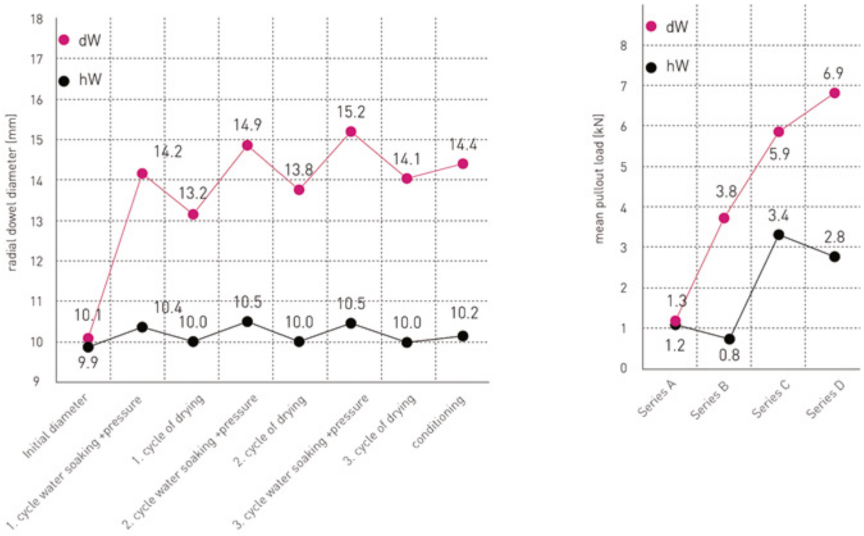


FIGURE 17 Comparison of hardwood- (hW) and densified (dW) dowel dimensions over several cycles of swelling and drying (left), and pull-out strength after 24 h (Series A), 48 h and accelerated ageing cycles (Series C and D) (right). Own illustrations after Mehra *et al.* (2021)

thus improving the mechanical properties of the entire DLT and DCLT systems (Lei *et al.* 2023). Thus, densified dowels can counteract many disadvantages when utilizing swelling by drying.

Densified dowels are unavailable in the construction industry. Thoma *et al.* (2019) emphasized that the persistence of the swelling pressure can be improved by utilizing densified dowels. Moreover, only a limited number of geometrical configurations and manufacturing technologies have been investigated for densified swelling connectors. However (Jung *et al.* 2008) found that dowel geometry and fiber orientation significantly influenced the structural capability of joints in densified wood. To augment the dimensional behavior of densified timber, in-depth characterization and a nonlinear model (Groenquist *et al.*, 2018; Cabral *et al.*, 2022; Lei *et al.*, 2023) would be beneficial. CNC-milling of connections allows for more geometric freedom in the design of connectors and expands the design space from cylindrical dowels to freeform connectors. Moreover, external connectors save material compared to integrated joinery because the cut-off is reduced (Joyce & Pelosi 2020). In particular, in CLT buildings, which can still be regarded as a relatively new construction method, developing new connection types offers great potential for further development and improvement (Ringhofer *et al.* 2018). In particular, the altered swelling characteristics of densified wood offer the potential for developing new external connectors (Mehra *et al.* 2021).

4 Discussion

The analysis of shrink-to-fit and swell-to-fit techniques in light of the currently available digital technology for material analysis, design, fabrication, and assembly reveals the potential and constraints for application in contemporary building practices.

The reorganization and reassembly of materials into EWP have expanded the construction possibilities of wood (Menges *et al.* 2016), enabling new connections, products, and structures. Digital tools can provide real-time feedback and precise coordination of manufacturing processes to achieve desired product shapes. Digital manufacturing considers the unique properties of each piece, anticipates dimensional changes and enables material-efficient designs using the dimensional changes in industrial joining processes. This could enhance the sustainability of building materials and structures owing to digital variations in traditional joining techniques for building elements and reduced material processing. The digital tools currently available for construction in craft and industry include digital scanners for material analysis, CNC tools for manufacturing elements, and robotic arms for assembling elements. Digital scanning technology is used in the timber industry to assess material properties and optimize the cutting of stock materials. Three-dimensional (3D) (Purba *et al.* 2020) and CT (Hansson *et al.* 2017) scanning methods are being developed to determine the moisture content and swelling ratios, allowing for a more detailed assessment of material properties. CNC machines are versatile and are commonly used in the timber industry (Vestartas 2021), presenting the opportunity to create individual and complex joint geometries (Kolarevic & Klinger 2013). Connections can be designed as DC and time functions, which can be implemented in parametric models. A closer investigation of the dimensional change in the densified elements can deliver the corresponding parameters. Moreover, reducing tolerance after joining is a tailored advantage of robotic assembly (Groenquist *et al.* 2018).

Shrink-to-fit techniques offer the potential to enhance the sustainability of building materials and structures owing to digital variations in traditional joining techniques for building elements and reduced material processing. However, extensive measures are required to implement these techniques in contemporary constructions. Long drying times, lack of structural data on shrink-fit joints, and limited dimensional stability of building elements have limited their utilization in industrialized buildings. However, there is potential for the production of EWP and/or its components, as these can reach EMC in a controlled environment, and settling and final dimensioning can occur before their use in structures. Here, a deeper investigation of special joint geometries integrating anisotropic shrinkage in their design, as used in log building, could provide valuable insights for future applications. This approach can potentially reduce the number of adhesives and nontimber connectors in EWPs and components. Moreover, all shrink-fit techniques show potential for application in low-tech structures with reduced subsystem requirements owing to reduced interoperability.

Using greenwood, especially hardwoods such as oak, requires less energy in the manufacturing process (Ross *et al.* 2007). However, linking these circular cross-sections is challenging. The design guidelines and formulas developed for underscribing and drawing can be transferred to other systems to provide insights into large-scale engineering structures (Ramage *et al.* 2017). Green roundwood also avoids the need for a sawmill, integrates the natural structure of trees, and reduces material use. Logs have superior structural capabilities to processed timber products, allowing for further material reduction (Vestartas 2021).

The two approaches by Wojcik (2020) demonstrated the feasibility of green roundwood and special joint geometries in digitally produced shrink-to-fit EWPs. Use cases, such as the application of clamping pressure investigated by (Renbutsu & Koizumi 2018) demonstrated the potential of combining crafting techniques with new materials such as resin. Further investigation into the compatibility of old techniques with new technologies and materials could reveal a new range of applications for these craft-based techniques.

Technically, implementing greenwood processing in digital building processes is not feasible yet. Necessary datasets containing fiber orientation or moisture content are often exclusively used in sawmills (Menges *et al.* 2016) and are not transferred further into the design or fabrication processes (Vestartas 2021). In addition, the individual processes that enable the utilization of DC have not yet been linked to an integral process. Constructive measures such as adapting building elements or using local tolerances could support shrink-to-fit techniques. A deeper investigation and documentation of log cabin building and greenwood framing techniques could provide valuable insights and knowledge for future applications.

Swell-to-fit techniques show great potential for joining timber elements and can enable a new level of timber design and engineering, considering the advantages of digital technology. Investigating traditional connector geometries and implementing swelling behavior into parametric models could facilitate the development of new connections and use cases for swelling connectors, providing the opportunity to reduce non-bio-based connectors further.

The use of pre-dried dowels in the industry demonstrates the successful transfer of craft-based techniques to contemporary buildings. Swelling dowels and robotic assemblies have already opened new design spaces, and structures are increasingly assembled automatically (Thoma *et al.* 2019), with timber joints requiring high accuracy and pressure during assembly (Apolinarska 2018). The swelling of timber can compensate for tolerances and tighten the joints (Ugolev 2013; Groenquist *et al.* 2018).

Moreover, the swelling behavior of the dried elements can be enhanced by combining them with compression. The transfer of the *kigoroshi* technique into contemporary building processes could enable the local manipulation of swelling behavior on an industrial scale. However, drying and compression face constraints from the overcompression of cells, resulting in structural issues for the joints (Langsner 1987; Groenquist *et al.* 2018; Sotayo *et al.* 2020; Cabral *et al.* 2022).

Densification can also be linked to these techniques, as heat and pressure are applied from the crafts. This development represents a valuable contribution to wood culture, as the drawbacks of other techniques are counterbalanced, opening new application opportunities for timber construction. Moreover, they have the potential to counteract drawbacks associated with these techniques. The more pronounced swelling behavior of densified timber shows superior qualities for use as a swelling dowel; densified dowels maintain swelling pressures and have improved mechanical properties and tight fitting owing to the shape-recovery effect.

Custom-swelling performance can be achieved by reorganizing material properties, and connections can engage the dimensional expansion of the material as a key performance characteristic (Correa *et al.* 2019). The altered swelling behavior and increased utilization of dimensional changes have the potential for further innovation. Swelling under a load with reliable pressure offers the potential for new joint configurations and use cases for external connectors, as the capability of densified timber has yet to be exploited (Cabral *et al.* 2022). Enhanced swelling properties are particularly advantageous in robotic assembly processes (Groenquist *et al.* 2018). Research on densified wood and its potential for hygroscopic joining is still in its infancy (Cabral *et al.* 2022) and has only been investigated in small-scale prototypes for slip joints and dowel geometries (Thoma *et al.* 2019; Sotayo *et al.* 2020). The structural capability of densified connections must be further assessed to allow their implementation in building codes and industry.

Despite this potential, previous research has mainly focused on eliminating moisture-dependent swelling using chemical additives and other methods rather than utilizing the enhanced behavior of densified wood for structural joints and connections.

Moreover, a review of other emerging non-adhesive joining techniques, such as wood nails and dovetail joints, suggests using advanced wood modification and machining technology to rejuvenate traditional wood-joining methods (Lei *et al.* 2023). The industry may benefit from the knowledge and skills of crafts. Some techniques, such as the IDS system, incorporate other crafting techniques. A closer look at the compatibility and potential of other techniques indicates that they have the potential to support the development of timber connectors further. Definite research gaps exist in scaling-up crafting techniques from furniture to building size. The local drying of elements, and thus exclusively the joining features, has not been investigated. (Amino 2004) showed the potential of drying prefabricated structural elements, reducing adhesives, and improving recyclability; however, the documentation lacks parameters such as moisture content and joint geometries.

Algorithms for arranging irregular logs and generating joinery can improve integrated design and manufacturing processes (Kirschnick, 2020; Vestartas, 2021). Parametric models can incorporate formulas, such as those of (Chambers 2006), to design connections with dimensional changes incorporated into parametric models (Groenquist *et al.* 2018). Computer-numerical-controlled (CNC) machines' geometric freedom and ability to process anisotropic materials enable various connection designs and use cases, promoting material efficiency and energy savings in building materials or component manufacturing.

Projects such as the prototypes by Correa *et al.* (2019), Wojcik (2020), Schmidt-Kleespies (2020) and Thoma *et al.* (2019) demonstrate the potential of implementing hygroscopic joining techniques in digital technology. They expanded the design space and construction possibilities of experimental timber architecture. The methods and techniques investigated show distinctive potential for implementation in contemporary technological trends and building processes.

Moreover, technologies to model the mechanical behavior of timber allow the prediction of its effective mechanical properties. Owing to the complexity of the material, advanced computational tools such as finite element analysis (FEA) or elastic limit analysis are required, which can be used to predict and consider multidimensional strength information at different scales of observation. This information can be implemented in design applications, paving the way for smart algorithm-driven processes following the vision of Industry 4.0, developing new wooden structural elements, and integrating wood analysis into the general concepts of computational design (Füssl *et al.* 2019).

5 Conclusion

The characteristics of wood make it an important component in sustainable construction. The historic use of wood in construction has followed a consistent pattern, focusing on reducing the material volume and enhancing efficiency. Despite improved tools and experience, these principles have remained unchanged over time. Using dimensional change for joining requires deep knowledge and understanding of wood, its anatomy, joinery culture, and timber construction. This is an integral part of the traditional woodworking practices. Two principles are primarily used for directional dimensional changes: shrink-to-fit and swell-to-fit. In particular, swell-to-fit with the additional use of dried and densified dowels has significant potential for use in monomaterial timber joints. We demonstrated the potential of using dimensional changes in construction to identify relevant knowledge gaps for future research. New digital tools present opportunities to preserve and translate traditional knowledge into new production techniques. This contributes to an ever-changing and evolving wooden culture (Fig. 18).

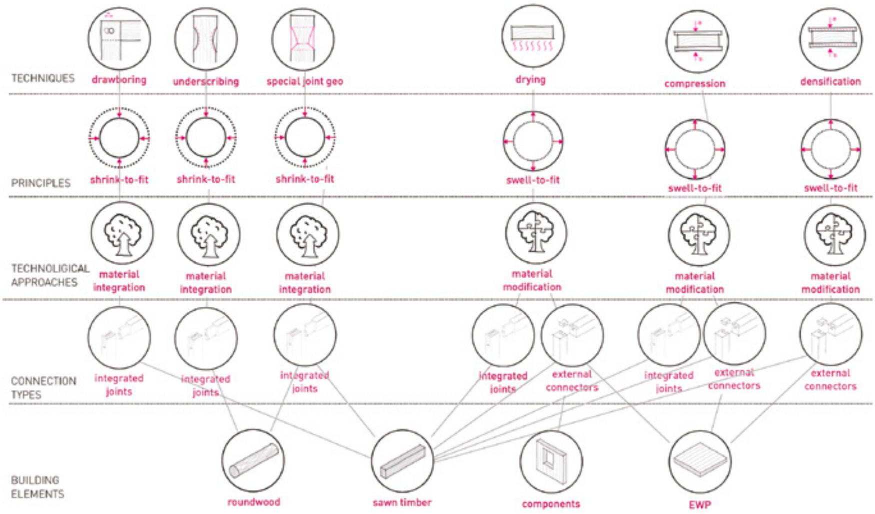


FIGURE 18 Diagram documenting relations between individual research results based on research matrix table with references (Table A1 in the Appendix). Own illustration

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Appendix

TABLE A1 Research Matrix: Principles, techniques, connection types, building elements and technological approaches in utilizing dimensional change of timber for joining

Principle	**Technique**	**Connection types**	**Reference**	**Building elements**	**References**	**Technological approach**
Shrink-to-fit	Droundboring	Integrated joinery	Sobon and DeStefano (2020)	Sawn timber	Ross *et al.* (2007)	Material integration
	Underscribing		Chambers (2006)	Round wood	Chambers (2006)	
	special joint geometries		Alexander (1978); Langsner (1987); Eckelman *et al.* (2004); Chambers (2006); Wojcik (2020)	Round wood Sawn timber	Eckelman *et al.* (2004); Chambers (2006); Wojcik (2020) Alexander (1978); Langsner (1987)	
Swell-to-fit	Drying	Integrated joinery	Seike (1977); Alexander (1978; Langsner (1987); Amino (2004); Mougel *et al.* (2011); Zwerger (2015)	Sawn timber	Seike (1977); Alexander (1978; Langsner (1987); Amino (2004); Mougel *et al.* (2011); Zwerger (2015)	Material modification
		External connectors	Zwerger (2015); Knapp Connectors (n.d.); Groenquist *et al.* (2018); Thoma *et al.* (2019); Correa *et al.* (2019); StructureCraft (2019); Covington (2020); Sotayo *et al.* (2020); van der Lugt and Harsta (2020); Pereira *et al.* (2021)	Sawn timber EWP	Zwerger (2015); Knapp Connectors (n.d.); Groenquist *et al.* (2018); Thoma *et al.* (2019); Correa *et al.* (2019); Sotayo *et al.* (2020); Knapp Connectors (n.d.); StructureCraft (2019); Correa *et al.* (2019); Sotayo *et al.* (2020);	

TABLE A1 Research Matrix: Principles, techniques, connection types, building elements (*cont.*)

Principle	Technique	Connection types	Reference	Building elements	References	Technological approach
					van der Lugt and Harsta (2020); Pereira *et al.* (2021)	
				Components	Schmidt-Kleespies (2020)	
	Mechanical compression	Integrated joinery	Satō and Nakahara (1995); Covington (2020)	Sawn timber	Satō and Nakahara (1995); Covington (2020)	
		External connectors	Berthold (1993); Moriyama *et al.* (2015); Thoma Holz (2018); Rombach Bauholz + Abbund (2019)	Sawn timber	Berthold (1993)	
				EWP	Thoma Holz (2018); Rombach Bauholz + Abbund (2019)	
	Thermo-mechnical compression	External connectors	Jung *et al.* (2008); Anshari *et al.* (2011); Groenquist *et al.* (2018); Sotayo *et al.* (2020); Mehra *et al.* (2021); Cabral *et al.* (2022)	Sawn timber	Jung *et al.* (2008); Anshari *et al.* (2011); Groenquist *et al.* (2018); Mehra *et al.* (2021); Cabral *et al.* (2022)	
				EWP	Sotayo *et al.* (2020); Cabral *et al.* (2022)	