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Split wooden rods for novel wood-based boards in the construction sector

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Abstract

Wood has been utilized as a building material for thousands of years. Nowadays, its renewable nature and carbon-storing capacity can become important factors in climate change mitigation efforts. This has led to a resurgence of timber engineering in recent years, with impressive multi-story timber buildings worldwide. However, it should not be overlooked that the wood sector will face several challenges in the coming years and decades to pave the way to a leading role of wood in the desired transition toward bioeconomy. Based on the assumption that an increasing demand for wood will make it a more precious resource, a couple of strains will emerge across the entire value chain of wood processing. This calls for innovations to address issues arising from predicted changes in resource provision, to increase material yields, and to promote reuse after the end of life. Our conceptual article proposes a new wood separation and processing method. This approach is inspired by the well-known production of wood shingles and is currently being developed for the implementation of new wood-based products.

Keywords: Wood; Separation techniques; Split rods; Wood-based products; Machine Learning.

1 Introduction

As measured by necessary and agreed steps of climate change mitigation, the construction sector consumes too much energy and emits a great deal too much greenhouse gases. In 2019, the global share of construction works and buildings amounted to about 35% of the total energy production and about 38% of the total CO_2 emissions [1]. Hence, there is an urgent need to turn the building sector into a carbon-neutral or even carbon-storage entity [2]. For the construction of buildings, intense research activities are currently focusing on reducing the emissions originating from the processing of building materials. Research on new concrete/cement formulations aims at reducing energy consumption and CO_2 emissions in the formation process [3-5]. Advanced manufacturing techniques and new design approaches are implemented to be able to use less material for the same function or performance and better recycling solutions are under investigation [6-8]. In the wood sector, approaches focus on the potential of accelerated use of timber to generate climate change mitigation effects by substituting more energy-intensive building materials such as steel and concrete with wood [9]. The cited study by Churkina and coworkers generated great attention but also catalyzed an intense debate, in which concerns were raised about its general feasibility. Such concerns included the potential incompatibility between a drastically increased resource provision and sustainable forestry practices as well as the amount of concrete that would need to be substituted with wood to become effective at a global scale [10].

As much as it is important to critically discuss the potential relevance and impact of certain measures, we believe that it is an intrinsic error of parts of the current scientific and public debate to play concrete and wood against each other. The urgent need to make the building sector carbon-neutral, or even carbon-negative, calls for radical and scalable innovations at both ends.

In this article, we point up some substantial challenges and opportunities arising from a drastically increased use of wood as a building material, from which we derive the need to be prepared for adaptations in the wood processing chain and to increase the palette of wood-based products, exemplarily illustrated in this concept paper by introducing a recent related research development.

Our initial analysis of future resource provision and consequences for the wood value chain focuses on Central Europe and while being aware that local conditions are substantially different in other parts of the world, we believe that there are common challenges, which implicate some overarching significance.

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1.1 The Resource Challenge in Wood Provision in Central Europe

Forests play a particular role in mitigation strategies against global warming as trees actively take up CO_2 and store carbon in wood (~250 kg carbon in one cubic meter of wood with a density of 500 kg/m^3). At the same time, wood is a key resource to help render the construction sector more sustainable, under the condition that felled trees are replaced by young ones, and the processed wood is used for a long time in construction [11-13]. However, a very large-scale wood provision by Central European forests may challenge sustainable forest management, and this situation can potentially become even more critical due to the impact of climate change. Predicted extreme weather events including drought periods will set trees under increasing stress and call for specific measures to retain and sometimes regain more stable forests with resilient ecosystems, including prevention of further biodiversity deterioration. Without a doubt, a more sustainable construction sector profiting from an increased use of timber products necessarily requires sustainable forest management. Given accelerating climate change, these more resilient and sustainable forests most likely build on a mix of wood species, rather than being monocultures [14,15].

More specifically, in Central Europe, but also in many other regions of the world, global warming will impact the current tree species composition of forests. In Central Europe established softwood species most likely will have to be replaced mainly with drought-resistant hardwood species. For instance, spruce, being a shallow-rooted wood species, is coming under increasing pressure from climate change-related drought periods, and subsequent bark beetle infestations, which have caused dramatic losses in recent years. Hence, forest management must react to these environmental constraints, aiming at more resilient and stable forests in the future, which may be dominated by different drought-resistant hardwood species, with additional diversification in age and quality.

The share of hardwood species is already increasing in central European forests (particularly beech), but in Switzerland, more than 70% of the hardwood is used to produce energy rather than for construction [16]. Hence, the predicted change in European forest composition toward more hardwood species will place great challenges on the woodworking industries in the construction sector. This is because highly developed wood products such as glulam and cross-laminated timber are predominantly made of softwood, in Central Europe mainly from spruce and the extensive use of multiple hardwood species in the wood construction sector is not yet established.

The increased availability of hardwood species like beech has prompted some efforts to utilize this wood for load-bearing applications, such as the so-called "BauBuche", a laminated veneer lumber (LVL) made of beech and other beech wood engineering products. These great innovations, however, cannot detract from the fact that the transition to hardwoods is challenging for established timber processing and wood construction chains. Procedures need to be adapted, for instance, due to less straight round wood, a higher density, and lower dimensional stability of some hardwoods (e.g., beech) compared to softwood species. Moreover, even some hardwood species like beech already show drought-related losses, and models of future tree species compositions of forests in Switzerland predict for the coming decades favorable growth conditions for hardwood species other than beech [17].

Climate change makes long-term planning for the wood processing and construction industry extremely difficult. In general, because of uncertainty about available species in the future given rapidly changing environmental conditions, and in particular, because of the high probability that wood species (e.g., drought-resistant hardwoods), which are less suitable for common processing routes and timber engineering products will become a major resource in wood production. Managing this transition requires new concepts to better adjust processing lines to hardwoods, which can cope with various wood species and varying qualities. One solution to this multifaceted challenge is to develop alternative processing routes and novel adapted wood-based products, which allow for large-scale production and possess mechanical and physical properties that can compete with state-of-the-art timber engineering products, respectively.

1.2 Alternative Separation Techniques

A change in timber provision will not only impact the resulting wood products but also the entire value chain including established wood processing procedures. This particularly applies to the sawmill processes, which have a sawn timber yield of about 60% in Switzerland [16]. The produced side products are processed further in wood processing streams, like the production of particleboards, fibreboards, and pulp, or for energy purposes. This suboptimal resource utilization with a partial loss of high-quality wood will be exacerbated by increased timber production and with an increased share of hardwood species because the processing of hardwood trees will most probably lead to even lower yields in sawmilling. In addition, a certain number of fibers are cut in conventional sawing processes, because the cutting kerf never exactly follows the fiber direction, which can result in quality losses [18]. Thus, in addition to the resource challenge as such, the technical and economic efficiency of the machining processes will become a major factor in the future. It is, therefore, necessary to develop new wood-based material concepts that are not only adapted to the predicted forest conversion but can contribute to the economic efficiency of the wood industry in the future. At the same time, these novel wood products need to be able to compete with established timber products.

The rather low yield in the sawmilling process and the increased availability of hardwood species have stimulated a search for alternative timber processing routes, in particular at BOKU, Vienna [18,19]. A very innovative non-cutting process, which has been developed recently is based on a squeezing and splitting treatment, resulting in so-called "Macrofibres" [20, 21]. These macrofibres possess excellent mechanical properties and can be processed to superior wood-based panels. However, the introduction of related wood products into the market is still pending. Other alternatives to the sawing process, which are based on a crushing and compression process and can process lower-quality wood grades, are the Scrimber process or the press-splitter process for small roundwood [18].

2 Split Wooden Rods Inspired by Shingle Production

The traditional method of shingle production is specifically established in the Alpine region for producing wooden roofs and facades. It is a highly interesting source of inspiration for the enhancement of non-cutting process technologies as it consumes very low amounts of energy, due to the easy fissility of wood parallel to the grain. Systematic experimental investigations on the fracture behavior have shown that the energy demand to split wood in the longitudinal/radial plane (fracture system TL) is particularly low [22], which explains the feasibility of the process. Moreover, the process allows for more efficient material utilization and produces wooden surfaces exactly along the wood fiber direction. Applying the traditional process, splitting is conducted manually with rather simple splitting tools, but on well-selected and straight softwood stem segments of ~15-50 cm in length, mainly larch or spruce wood. In industrial processes, shingles are produced very efficiently with high throughput using pneumatic splitting tools.

This non-cutting, shingle production process can inspire the development of a new type of wood-based products. With an analogous processing method, up to ~1 m-long stem segments can be split into several rods of the same length. However, since conventional shingle production uses high-quality and straight softwood to split very smooth and planar surfaces, certain process adaptations are required to split rods from 1 m-long hardwood stems of lower quality. Depending on the cross-sectional dimensions of the stem segment, the process can be started from the entire logs or after a half-cut or quartering of the logs. The adapted process requires two subsequent splitting steps, which can be conducted at the laboratory scale in a conventional, but adjusted wedge-splitting machine, (1) splitting into radial boards, followed by (2) tangential splitting into rods of targeted dimensions. At lab-scale, a common wedge-splitting machine can be adjusted with a multi-blade splitting tool head to produce in either step, several radial boards and subsequently several rods, respectively. After splitting, the remaining bark and other loose parts such as dead knots can be easily removed. The as-produced rods have a cross-section of approximately 25 x 25 mm. Figure 1 shows the splitting process at the lab scale.

Figure 1. Splitting process in a conventional splitting machine with a modified, multi-blade splitting head resulting in split rods for further processing.

2.1 Wood Rod Processing

The wooden rods obtained by the shingle production-inspired process have a perfectly aligned fiber orientation, therefore strength and stiffness of the single split element should be competitive to those of sawn timber elements, based on former comparative studies [18]. However, the simple splitting process results in uneven cross-sectional dimensions over the length of the rods and uneven surfaces. Compared to standardized, rectangular cross-sections and planar surfaces of commonly used wooden lamellae for timber engineering elements, the further processing of the obtained rods to engineering products requires more sophisticated technological steps.

The irregular shape of the rods is a particular challenge for the analysis of (mechanical) properties of the individual elements and their strength prediction as well as the assembly of the split rods to obtain wood-based boards. Uneven surfaces and changing dimensions, (even combining different wood species with different densities and qualities), call for new sophisticated approaches in wood analysis and grading. In this regard, Machine Learning can help better predict wood rod properties and convert the obtained data into valuable information for the optimization of process parameters and board products. The data-driven approaches, especially deep neural networks-based tools, can find highly complex and non-linear patterns in data of different types and sources. The trained models can be applied for the detection, classification, regression, or forecasting of properties [24]. Thus, these systems are very well suited for the optimized processing of split rods from different species since they allow for high-throughput identification and quantification of essential features along the entire processing and product development chains [25]. The necessary Machine Learning algorithms are currently developed and written in Python with the help of dedicated open-source libraries such as Keras, TensorFlow, and Scikit-Learn.

In Figure 2 the envisioned ML-supported process is illustrated. As the rods are placed on a conveyor belt, an automated camera system, activated by a light barrier, captures high-resolution images of each rod. These images are employed as input data for a convolutional neural network, enabling the prediction of strength and stiffness values for each rod, regardless of size, shape, or wood species. During the initial phase of the project, strength and stiffness values are derived from mechanical testing of the rods. These values act as ground truth labels during the training phase, enabling the Convolutional Neural Network (CNN) to make robust predictions that align closely with the actual mechanical properties of the rods, even when dealing with a variety of wood species.

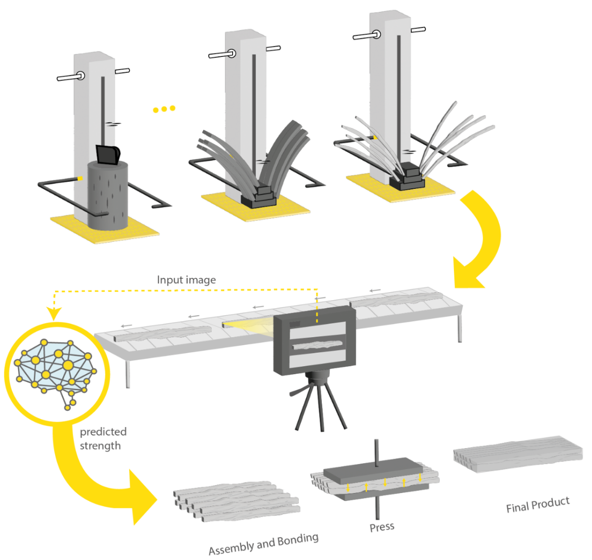

Figure 2. Schematic illustration of the planned ML-supported processing from split rods to wood-based products.

The final assembly of split rods to a wooden board with superior and predictable mechanical properties is another critical part. Here, wood-based products like Glulam and CLT profit from the easy stacking of rectangular wood lamellae and well-established wood grading technologies, allowing to predict the strength of each lamella usually from the same wood species [23]. This enables an optimized positioning of lamellae in wooden beams or solid wood boards and the reliable calculation of the load-bearing behaviour.

The prediction of the final mechanical properties of rod-based boards using Machine Learning models will be grounded in structured (tabular) data as input. This data will encompass precise information about the arrangement and orientation of rods within the laminated or ply-assembled boards in the composite, as well as the predicted strength of individual rods derived from the convolutional neural network model. Additionally, it will incorporate various parameters related to the production process, including factors such as adhesive, pressing pressure and time, etc. The research into Machine Learning (ML)-supported product quality control can draw valuable insights from previous studies focused on the real-time prediction of strength properties in wood fibreboards. These former studies successfully integrated data related to raw materials and the entire processing infrastructure, demonstrating the viability and effectiveness of this approach [26].

2.2 Process towards wood rod board production - First Results

While the Machine Learning-assisted split rod grading and board assembly is currently developed in the framework of the ETH-Domain project MainWood, we made first tests to produce boards at the laboratory scale without rod grading and a non-optimized rod assembly for a first assessment of the range of achievable mechanical properties.

Stem segments of beech were split as discussed above and obtained rods were stored under standard conditions (20 °C, 65% relative humidity) before further processing. Due to limitations in press size to produce lab-scale boards, the length of the rods had to be shortened to 53 cm to fit a mold produced for the test trials. Two layers of rods were placed into the press mold and glued together by using resin and hardener of the 3-component system SikaDur®-42 LE Plus provided by Sika Technology AG (Zürich, Switzerland). The pressing force was around 8.8 MPa for 4 hours followed by 4.4 MPa for 3 hours. After board conditioning, 3-point bending specimens of dimensions 500 x 50 x 24 mm3 were cut. The height varied between 22 and 25 mm due to the uneven cross-sections of the rods. The specimens acclimatized for another 7 days at 20 °C, 65% relative humidity before testing. Bending tests were conducted according to DIN EN 310 (1993).

Figure 3 shows the testing setup and the force-displacement curves obtained in the three-point bending tests as well as the mean and standard deviation of density, elastic modulus, and bending strength of the composites.

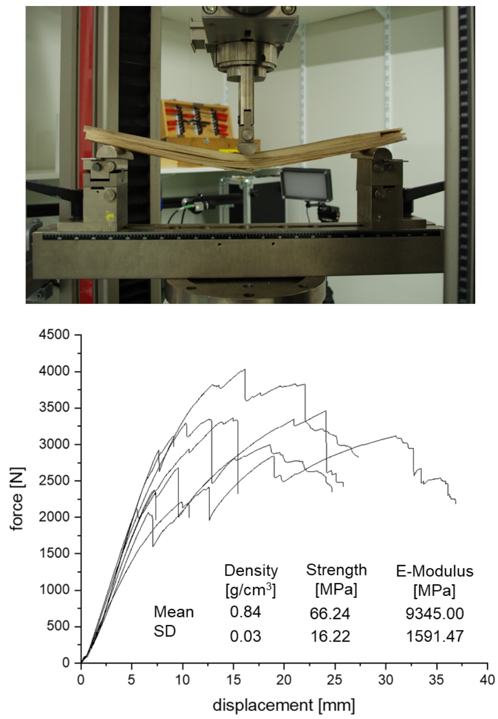

Figure 3. Upper image: Three-point bending setup with a fractured specimen; lower image: Force-displacement curves of eight specimens cut from the beech rod board and respective statistical analysis.

The density is at the upper bound of the range of natural beech wood [27]. The higher density can be attributed to the addition of the adhesive and/or a certain compaction of the beech rods in the press. The mechanical properties obtained in these initial tests are higher than those of wood-based boards, like oriented strand board (OSB) [27], but the density of the rod-based board is higher, and it was made of continuous rods, which will not be the case for larger boards after scaling. In comparison to the abovementioned "Macrofibre" boards [21], the bending strength is at the lower end of the indicated property range of boards with the same density that were bound with phenol formaldehyde resin (PF), while the mean elastic modulus is below this property range. However, further property improvement of the rod-based boards is possible in terms of specimen grading and assembly as well as bonding of the board. This should not only increase absolute values but also reduce the standard deviation, making the boards more reliable in construction.

3 Perspective

The preliminary tests indicate that split rod boards, which could potentially be produced from various hardwood species of lower quality grades, may have the potential to fill an important gap in wood construction. Cross-laminated timber has superior properties, but the above-mentioned resource efficiency issue. Oriented strand boards (OSB) possess much higher resource efficiency, but the properties cannot compete with solid timber products. The split rod boards may be as resource-efficient as OSB and can potentially reach mechanical properties close to some solid-wood products. Efficient production of curved elements and ply assembly of rods into boards, analogous to plywood and cross-laminated timber can further increase the design freedom.

For the preparation of boards, the split rods can be bound by common resin systems or for hybrid elements by mineral binders. Epoxy resins, as used in these preliminary tests, have the advantage that they are less sensitive to larger gaps between rods, which are a consequence of the uneven cross-sections of the rods. Ideally, in the future, fossil-based synthetic resin systems can be replaced by bio-based binder systems with a similar performance to produce a fully bio-based composite with targeted properties [28].

It is important to emphasize that the introduced approach towards novel wood-based panels is still in its initial stage and key challenges in production efficiency, scalability of processes, predictability, and reliability of properties as well as logistics still need to be tackled. However, the concept bears the potential to offer an alternative solution for wider sustainable utilization of wood given the increasing impact of climate change on forests and the building sector.

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Conflict of interest

A patent application on rod-based wood materials has been filed in 2022.

Authorship statement (CRediT)

Ingo Burgert: Conceptualization, Writing – Original Draft, Writing – Review & Editing, Supervision, Funding acquisition. **Sebastian Kegel:** Investigation, Formal analysis, Writing – Review & Editing. **Thomas Schnider:** Investigation, Writing – Review & Editing. **Julia Achatz:** Visualization, Writing – Review & Editing. **Sandro Stucki:** Investigation, Writing – Review & Editing. **Mark Schubert:** Conceptualization, Writing – Original Draft, Writing – Review & Editing.

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