Approaches for the Use of Rapidly Growing Willow Rods in Earth-Based Construction

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Abstract This chapter investigates construction applications of natural fibres and fast-growing plant-based materials, which can be processed into load-bearing components using specially tailored digital manufacturing technology. The sourcing and production of the developed sustainable and recyclable freeform lightweight structures based on willow and earth are described in detail and material samples are shown. At the end-of-life, the components can be disjoined and the composite materials in the components can be fully separated mechanically for composting, recycling or incineration. Moreover, the developed structures were prototyped, implemented and tested in full-scale research demonstrators at the 2023 German National Garden Show in Mannheim (BUGA23). With this contribution we show the feasibility of such novel robotic construction methods of biogenic materials in structural applications for the first time. The envisioned application potential lies particularly in the new construction of residential buildings, hotels, office buildings and buildings with similar uses.

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13.1 Introduction

The European Union is approximately 43.9% covered by forest and other wooded areas. Finland and Sweden have the largest share of this, whereas Germany ranges in the middle with a forested area of 30–45% [1]. At the same time, Germany was the largest roundwood producer in the EU in 2020 and shared the leading position in sawn timber production with Sweden [2]. Although wood is a renewable resource, with a rotation period of 30–140 years, it is not an unlimited resource. Despite high and overall increasing production figures, domestic wood quantities are not sufficient to meet European demand, which is why the material is imported into the EU from all over the world [2].

According to a WWF study, global wood consumption in 2020 was between 4.3 and 5.0 billion cubic meters, far exceeding the globally sustainably cultivated amount of around 3.0 billion cubic meters. The consumption trend here is increasing, although the risk limit of 4.2 billion cubic meters, which entails significant sustainability restrictions, has already been exceeded [3]. Moreover, timber is frequently utilized in engineered wood products which contain glues and adhesives. These high-performance materials are energy-intense to produce and are created from a combination of natural and fossil resources. Furthermore, energy recovery is the sole end-of-life option for these products (see Fig. 13.1).

Thus, other approaches are required either to reduce the demand or to develop other renewable materials for construction purposes in order to meet the demand. For this, willow as a fast-growing natural raw material seems suitable to replace wood that is not infinitely available or other construction materials that have a high environmental impact.

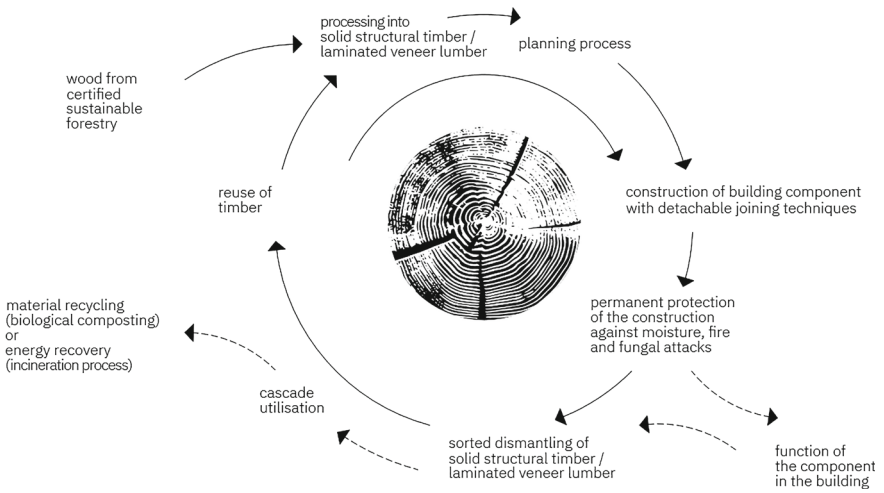


Fig. 13.1 "Circle" of wood. *Copyright* KIT Professorship of Sustainable Construction

Willow is a pioneer plant settling which colonize areas that are poor in nutrients and water and can quickly regenerate after strong environmental influences such as flooding. Their cultivation therefore does not (directly) compete with other agricultural products, which further underlines their importance for sustainable use of resources. Due to its rapid growth and short rotation periods of up to 30 years, willow is now mainly cultivated for energy production purposes [4] and harvested in 1–5 years short rotation cycles, depending on the intended use [5]. Construction purposes are not considered yet. Moreover, when willow is used in building components, the aim is either to reclaim it from the component and use it in other wooden application as a filling material or biodegrade it after it reaches the end of utilization cycle as a construction/product material.

Clay is a traditional construction material with high local availability [6]. It can be recycled infinitely [7] and can be processed and manufactured as a secondary building material in the same quality as the primary material [8]. To ensure optimal and efficient recyclability of the clay mixture, leaching processes can be used to separate mineral and plant additives. Alternatively, the organic fraction can remain in the material mixture (see Fig. 13.2).

A combination of both willow and clay is envisioned for innovative construction elements, that are less energy and emission-intense in production than conventional construction elements from concrete, faster regrowing than wood, potentially locally sourced, not harmful to nature, enabling rewetting of agricultural land and are fully recyclable. To achieve this, the research projects ReGrow [9], WillowWeave and ReSidence [10] developed a holistic experimental and digital construction approach within an integrative co-design process in order to produce such a construction component of a willow-clay composite on a 1:1 scale.

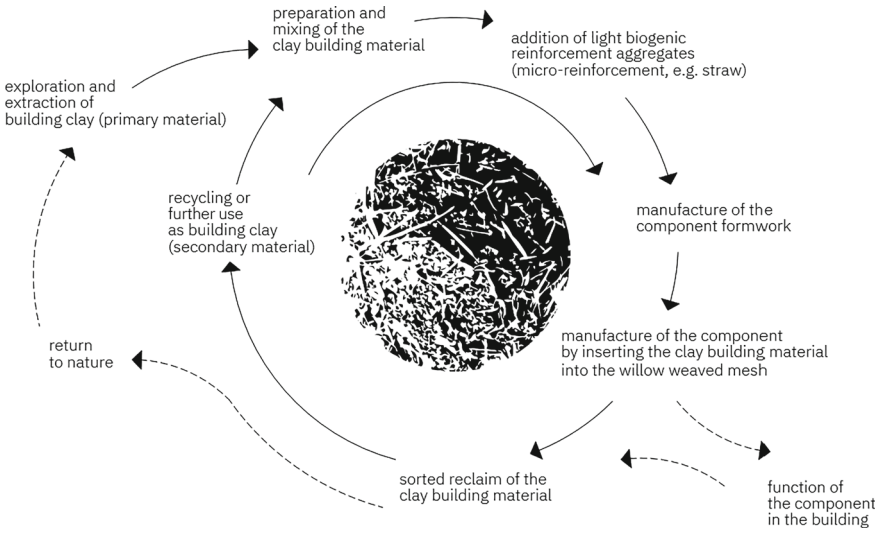


Fig. 13.2 "Circle" of clay. *Copyright* KIT Professorship of Sustainable Construction

13.2 Method

The aim was to develop circular construction methods based on regional materials and to create functionally integrated lightweight structures for use in construction. The design principles should make modular combination of the resulting components possible and special attention was paid to concepts for the subsequent use of the structures. Central elements that contribute to this goal are the following three design and manufacturing processes:

- Bespoke computational design and fabrication solutions to enable free-form wound lightweight structures based on the combination of willow and clay as natural sustainable materials.
- Robotic fabrication methodology for implementing weaved willow tree branches.
- Lightweight wood construction.

The aim was to investigate construction applications of fast-growing plant-based materials, which can be processed into load-bearing components using specially tailored digital manufacturing technology. For this, the whole life cycle of the building component was designed (see Fig. 13.3) for flexibility and circularity. When designing buildings and their components, maintaining material cycles through the detachability of materials and their joining techniques play a crucial role in order to be able to continue using the resources as well as maintaining their values and material quality as much as possible. Thus, the separability and recyclability of the used material were a critical aspect.

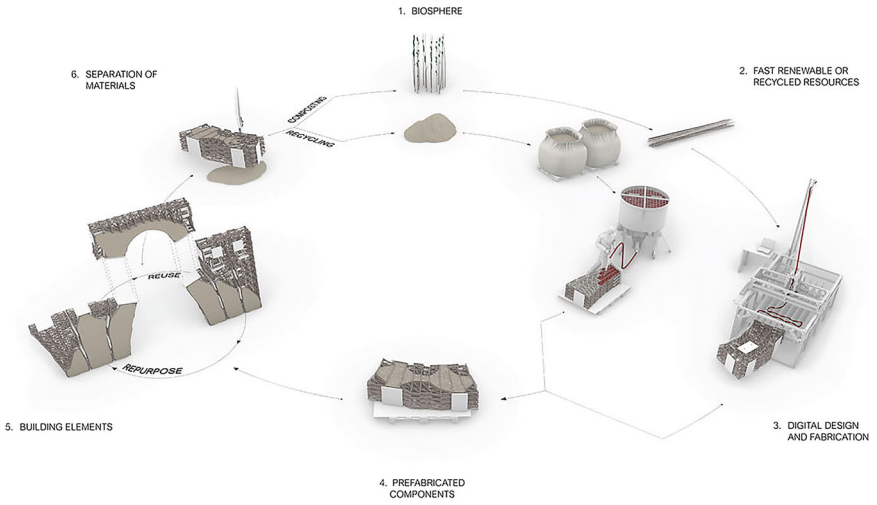


Fig. 13.3 Life cycle of willow-clay-composite from sourcing, production, use to end-of-life and a new cycle

Moreover, the resulting lightweight structures were assessed with respect to environmental impact categories, e.g. greenhouse gas emissions, and compared to conventional constructions of the same load bearing capacity and showed promising results.

The harvested willow rods (1. and 2.) are made flexible for weaving in a dampening or watering process. Then, they are coupled and additively fabricated by a custom machine to baskets (3.) that are then filled with moist earth. Finally, the prefabricated building components (4.) are drying for several weeks for hardening. The basket weaving and components can be built in any shape required for loadbearing structures (5.). For installation, the prefabricated elements are joined onsite with a crane and can be easily disjoined (6.). At the end-of-life, earth and willow can be separated mechanically, where the biogenic share can be utilized as biobased filling material in other applications, or alternatively composted or incinerated and the earth can be directly recycled.

The development was driven forward by interdisciplinary co-design workshops and supported by bespoke manufacturing technology for the production of the components. To achieve this, a comprehensive fabrication system was developed, starting with a two-axis machine capable of extruding and depositing continuous willow-jute composite strands made from spliced willow branches using additive techniques. Controlling the machine's extrusion, movement, and deposition path proves challenging due to factors such as the flexibility and varying thickness of willow branches, as well as the requirement for tensioning in the final components. Moreover, challenges due to low local availability of willows (unexpected high market demands), or variability of biogenic raw materials had to be faced and mastered.

13.3 Solutions

On the one hand, a bespoke design-to-manufacturing process [11] for the use of fast-growing willow tree branches was expanded and adapted in order to implement lightweight structures in the future construction industry not only in an material-efficient manner, but also on the basis of renewable raw materials. On the other hand, an approach to digital fabrication for structural applications was developed. This includes both the development of a new type of construction and design repertoire and the implementation of corresponding machine technologies for the production of load-bearing components. Both design ideas are combined in a complementary manner to create a modular concept for producing functionally integrated building components from renewable raw materials.

Figure 13.4 shows the necessary pre-processing of the willow rods to make them useable for robotic weaving processes. It includes planting and harvesting, damping or watering and the production of endless strains for the robotic weaving process. During the fabrication of the building components, a stabilisation by metal forms is provided which can be reused afterwards. Moreover, engineering wood products

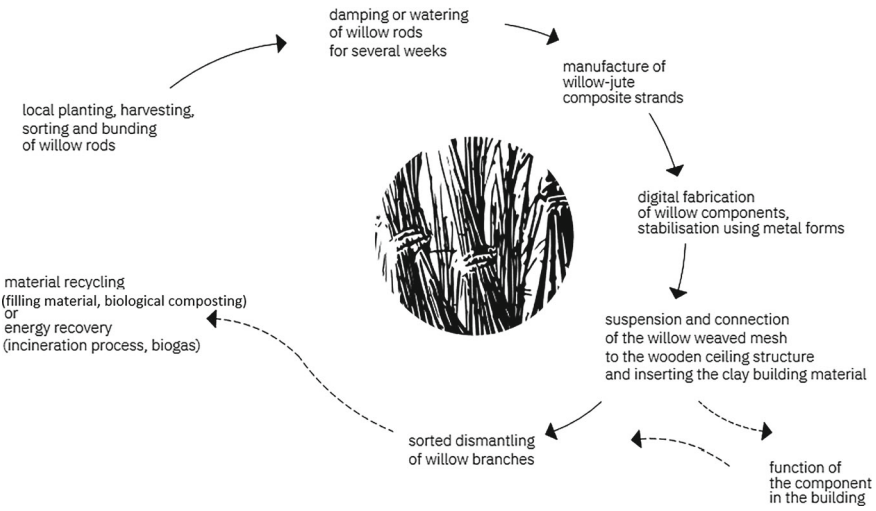


Fig. 13.4 "Circle" of willow. *Copyright* KIT Professorship of Sustainable Construction

are used to stabilize the whole component and to enable the clay filling. Then, the willow baskets are connected to each other and the demonstrator is manually filled with the clay building material including light biogenic reinforcement aggregates. Finally, the composite elements are dried for several weeks and then transported and erected with a crane onsite using steel ring screws, that can be detached after the modules reach their final position.

After use, a full recyclability of the elements is envisioned. The clay can be recycled and reprocessed to secondary building materials, but for the willow rods, after their recovery from the component one option is a post-treated utilization as organic filling material to keep the biomass in the technosphere. When reaching the last use cascade level, the end-of-life biological compositing turns willow into organic material and returns it to biosphere. The engineered wood products' recycling depends on the availability of local material recovery plants (crushing, sorting), the demand for this material as well as the used adhesives which would often lead to energy recovery as the most likely end-of-life scenario.

As part of the research, two sustainable and recyclable lightweight structures were developed and produced, erected and tested with full-scale research demonstrators at the 2023 German National Garden Show "Bundesgartenschau BUGA23" in Mannheim (see Fig. 13.5). Moreover, the willow-clay building demonstrator was expanded to investigate the research focus on local energy generation and microclimate adaptations. Information events, visitor surveys and an international symposium took place at the Federal Garden Show to give a large audience an insight into the research topic of sustainable and digital construction.



Fig. 13.5 Willow earth composite elements in detail and full-scale demonstrators at Bundesgartenschau Mannheim 2023 © KIT/IIP and KIT/IEB

13.4 Conclusions

Thanks to the current state of the art, robotic freeform winding can already be used to produce topology-optimized and low-waste lightweight structures based on natural and energetically low processed raw materials. This composite development represents a further step towards the sustainable construction of tomorrow. Future applications in residential buildings, hotels, office buildings and similar usages are envisioned and can cover a considerable share of new construction demand. By further

developing the process technology to meet the special requirements of reinforcement made of biogenic sources like natural willow tree branches, sustainable load-bearing structures should be produced on a larger scale, something that has not been technically feasible to date. In addition, regionally available, rapidly renewable raw materials are being made usable for scaled applications. For this, the sustainable sourcing of willow and earth needs to be addressed with respect to an industrial scale production, since both willow short rotation coppice production facilities as well as clay mines need to be ventured. However, this is necessary support the transition to a circular economy in the construction sector and further reduce the CO_2 footprint of lightweight structures. At the same time, state-of-the-art digital design and manufacturing processes are being used, which guarantees high material efficiency and leads to a high potential for the future of the construction industry in terms of economic utilization.

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