Towards Construction 4.0: Computational Circular Design and Additive Manufacturing for Architecture Through Robotic Fabrication with Sustainable Materials and Open-Source Tools

Philipp Eversmann and Andrea Rossi

Abstract There is a constant increase in demand for new construction worldwide, which is one of the main contributors of worldwide CO_2 emissions. Over the last decades, such increase led to scarcity of raw materials. Although design methods have been developed to increase material efficiency, this has not yet led to a widespread reduction in material consumption. This is due to a variety of factors, mainly related to the inability of conventional fabrication methods to produce the complex shapes that result from such computational methods. Industrial robots, while offering the potential to produce such optimised shapes, often rely on inflexible interfaces and highly complex industry standards and hardware components. In response to this dual sustainability and technology challenge, this article describes a series of research projects for the design and manufacture of architectural components using renewable materials and robotics. These projects are based on novel additive robotic building processes specifically designed for renewable and bio-based building materials, ranging in scale from solid wood elements to continuous wood fibres. We propose methods to optimise the distribution of such materials at their respective scales, as well as manufacturing methods for their production. In this context, the use of novel and automatable joining methods based on form-fit joints, biological welding and bio-based binders paves the way for a sustainable and circular architectural approach. Our research aims to develop intuitive open-source software and hardware approaches for computational design and robotic fabrication, in order to expand the scope of such technologies to a wider audience of designers, construction companies and other stakeholders in architectural design and fabrication.

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United Nations' Sustainable Development Goals 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns · 13. Take urgent action to combat climate change and its impacts

1 Introduction

1.1 Construction Technologies and Sustainability

There is a constant and growing increase in demand for new construction worldwide, which is one of the fundamental drivers of increase of atmospheric CO_2, and hence one of the leading causes of climate change [1, 2]. Over the last decades, such increase and logistic limitations led to scarcity of building materials [3]. This is also partly because massive construction techniques remain the most popular choice of construction [4, 5]. Instead, circular construction techniques, material-saving design methods, and manufacturing processes based on renewable, carbon -storing resources [6] are required.

1.2 Renewable Materials

Since afforestation is not infinitely scalable, additional fast-growing renewable resources are needed. Novel construction techniques with bamboo can be mentioned [7, 8], but unfortunately the material mainly grows well in Asia and south America, leading to a large impact of transportation in a Life-Cycle Assessment for other countries [9]. An alternative, which can be grown in Europe, are willow rods, which can be processed into filaments for additive manufacturing and textile architecture [10]. Natural fibres have good structural properties but are energy intensive to produce, resulting in a positive carbon footprint [11]. The fibre/resin ratio of 30–40% [12] is significantly lower than the material/adhesive ratio in engineered timber products (85–98%) [13]. Recently, construction techniques with mycelium, the root network of fungi, have been developed, i.e. as insulating material, plaster base [14], and mycelium bricks [15, 16]. Even intelligent behavior of mycelium in architecture and buildings is investigated [17, 18]. First companies are developing mycelium-based products, as acoustic elements, and floor panels [21].

1.3 Towards Construction 4.0

Definitions. The term "Industry 4.0" was coined in 2011 as part of a high-tech strategy project of the German government that promoted the computerisation of manufacturing [22]. In this perspective, information and communication technologies such as the Industrial Internet of Things (IIoT) will enable automated, responsive manufacturing in high volumes and with a high diversity of variants. Although there is no single definition of "Construction 4.0" (C4.0), it seems to revolve, similar as Industry 4.0, around a decentralised connection between physical and cyberspace through ubiquitous connectivity. However, C4.0 is not limited to these technologies but draws on a broader spectrum, the most important being Building Information Modeling (BIM), Additive Manufacturing (AM) and Cyber-Physical Production Systems (CPPS) [23]. The great promise of C4.0 lies in the almost complete automation of the entire project life cycle, not only through highly efficient design, fabrication and material use, but also enabling circular construction through digitally traceable reusability of components, material flows and recycling processes [24].

Current state. Digitization in planning has already advanced compared to construction, due to its complexity with many sub-systems, materials and details. Automation of existing processes is often still very difficult and inefficient, being originally designed to be carried out manually. Although little has yet reached construction sites, significant progress has been made in researching novel robotic construction techniques [25, 26]. Due to a strong acceptance and long history of digitization, timber construction is nowadays the most automated building sector [27], with a seamless integration of existing processes as well as new technologies [28, 29]. Automation in concrete construction is generally much lower. Examples are precast building parts and semi-finished components, such as partially precast slabs [30]. The most substantial digital advancements can be found in entirely new construction processes, as 3D printing through extrusion. Besides a series of attempts in the last decades [31, 32], automation in masonry construction is still hardly used, with the exception of prefabricated walls parts [33]. In steel construction, formatting is mostly automated, while assembly and welding are still performed mostly manually. Research is being done on form-fit steel connections [34] and additive manufacturing with steel, and automated assembly and welding for large structures [35, 36].

Key technologies: BIM and Computational Design. Building Information Modeling (BIM) is a concept of associating all kinds of data to 3D Models of buildings [37]. Within C4.0, the major challenges are the successful integration and management of data over the whole conception, planning and life cycle, including the tracing of materials and components in accessible databases to enable digital circular design flows, the integration and merging of Computational Design (CD) with BIM, and the integration of design to fabrication workflows. The term CD is commonly used for design methods associated with scripting, parametric modeling and all kinds of digital form finding methods [38]. Towards a "Computational BIM", two approaches are currently pursued: one is the integration of parametric modeling and simulation in one large software package [39], the other one is creating software bridges, allowing to freely combine multiple smaller packages for their respective strengths [40].

Key technologies: Additive Manufacturing. Subtractive machining processes describe an approximation to the final contours of a workpiece by material removal. Formative manufacturing processes are a volume-constant change in the workpiece geometry [41]. Additive manufacturing processes, on the other hand, describe the successive construction of a workpiece by adding individual elements or layers [42]. In the construction industry, additive manufacturing techniques are currently most advanced in concrete construction with already available solutions on the market [43–46]. In steel construction, first prototypical projects exist, showing the potential for larger-scale applications [47, 48]. For timber construction, research is done on extruding timber particles with different binders [49, 51, 52]. For small-scale applications for design and prototyping polymer-based filaments exist and applications for replicating the textures of wood are available [53, 54]. In the literature, the term "additive manufacturing" or "additive construction" has been broadened to include also assembly processes as in robotic timber construction, referring to the additive nature of the process in contrast to subtractive processes as CNC milling [55–57].

Key technologies: Cyber Physical Production Systems (CPPS). CPPS link real (physical) objects and processes with information-processing (virtual) objects and processes through ubiquitous information networks [58], such as production systems with sensors and feed-back processes, capable to adapt to collected data or provide human interactivity. An example of this is an assembly system we developed for irregular wooden shingles for façades, where geometry scans are sent to a connected computer, which calculates a desired position and sends the data back to the robot for execution [59]. Unlike repetitive processes of past industrialization [60], C4.0 requires highly adaptable workflows. This requires highly accelerated time intervals in which automation systems must be adapted and changed. CPPS promise to achieve these formerly extremely difficult tasks through new sensor technology, kinematic simulation, coding technology, a wide range of industrial components and the ability to create industrial networks with customisable functionality. In the following sections, a distinction is made between the kinetic simulation needed for the conception of CPPS, and the additional control mechanisms of the various components for robotic tools and processes.

Kinetic Simulation. In CPPS, automation needs to be flexible to accommodate for highly variable components. Therefore, kinematic simulation techniques are necessary to plan the robot motions, check for reachability and prevent collisions. Most manufacturers provide their own kinematic simulation software, as ABB RobotStudio [61], KUKA.sim [62], Fanuc Robotguide [63] and Universal Robots URSim [64]. Also, manufacturer independent commercial solutions exist, as Visual Components [65], Gazebo [66], CoppeliaSim [67], HAL Robotics [68] and RoboDK [69]. There are also a range of software solutions developed by research institutes, often based on Rhinos Grasshopper interface, as Robot Components by University of Kassel [70], Compas FAB by ETH Zurich [71], KukaPrc by RobArch [72] and robots by the Bartlett [73]. Research for the development of new robot systems is mainly done using the Robot Operating System (ROS) for programming, path planning and direct robot control [74]. Here, it is also possible to use automated path planning algorithm packages such as Moveit [75].

End-effector design and control. C4.0 requires fast adaption of processes and new robotic tool development. Current industrial automation engineering approaches are very time-consuming and expensive, and few plug-and-play products exist. Therefore, fast, adaptable, configurable prototype-able and cost-effective approaches are needed. This concerns both the communication with the different end-effector components as sensors, moving parts, etc., and the fabrication of the tool. Depending on the task, these components can be differently combined, as i.e., an intelligent industrial camera to detect an object position, and a pneumatic gripper to pick it and place it to its final position. Most components can be controlled by a simple on/off mechanism through digital IOs (Input/Output) [76], as pneumatic valves, simple sensors, or actuation of an electric device. For more complex control, as i.e., controlling the speed, timing etc. of a stepper motor, open-source electronics platforms such as Arduino can be used [77]. These allow for preprogrammed behaviors, which can be further integrated with signals from the robot control system. Also, analog IOs [78], and older protocols, such as serial messaging, can be used for transmitting the actual values of sensor data [79]. Most robot controllers provide I/O boards, to which the tools and sensors can be hardwired. Newer BUS systems as IO-LINK using industrial networks can be digitally configured and require less hard-wiring [80], even via wireless industrial networks [81]. Some systems require more direct tool control and data transmission, which can be achieved through direct connection to the axis computer for real-time adaption, which can be necessary i.e., for force-sensing and adaption [82].

2 Aim/Motivation

The aim of this article is to describe methods to combine these recent advancements in computational design, digital fabrication and robotics with the requirements to reduce material usage, rely on biological and renewable processes, and develop circular design systems. This is achieved by directly linking digital fabrication processes with computational methods for material optimization, as well as adapt them to the unique characteristics of fabrication with renewable, bio-based and living materials. Furthermore, circular strategies for reuse, and for recycling and compositing at end-of-life, are achieved by developing reversible and/or bio-joining systems between elements of a construction system. This is supported and enabled by the development of an adaptive and intuitive robotic programming and actuation framework, relying on open-source software and hardware tools.

The article is organized as follows. In Sect. 3, we present computational design methods for circular and material-efficient components and corresponding robotic fabrication technologies. In Sect. 4, we present a series of case-studies, ranging from discontinuous material placement, as robotic assembly and joining techniques for timber components, to continuous assembly, as veneer winding, additive manufacturing with timber filament, biofabrication with timber reinforced mycelium and compressed bio-bound wood particles. These case-studies are ordered through the scale and resolution of used materials. In Sect. 5, we conclude by highlighting the potentials of the described approach, as well as identifying the further steps to enable a more direct connection between sustainability goals and digital fabrication strategies.

3 Methods

3.1 Computational Design Methods

We apply computational design logics at three different levels: firstly, through a comprehensive circular design approach at the component level and in material selection; secondly, through optimization methods for material distribution within the components; and thirdly, by organizing the information of our design models directly for robot manufacturing.

Circular Design Approach. We define a circular design approach through a holistic integration of the following topics: a computational modular design approach for building components, and a structured choice and characterization of material systems in relationship with their digital processing, assembly and joining technologies, grading and up/recyclability. Instead of highly specific, single purpose building components, modular design systems are developed to allow for elements which could be potentially reused multiple times in different circumstances. While modular same-sized elements often result in uniform designs, computational combinatory logics enable high level of variation in the final assemblies, using only minimal number of component types (see Fig. 1).

Furthermore, often current approaches to modularity rely on a small number of identical components applied in a variety of different conditions within the assembly, often resulting in over-dimensioned elements, and hence high levels of material waste. A more material-efficient approach to modularity, as we propose it, is to assume the outer geometric form and interface areas of components as fixed, but to then develop methods to customize its internal structure to the unique needs of each component, given its specific structural and environmental requirements in its location within a larger assembly. However, when aiming for higher customization within a circular material system, particular attention must be placed on the material assembly and joining techniques, to ensure both reversibility of assembly and recyclability and/or composability of the components within their life cycle. For this reason, we understand design of components as the combinatorial integration between material, binding/joining techniques, fabrication technologies and specific performance requirements (Fig. 2).

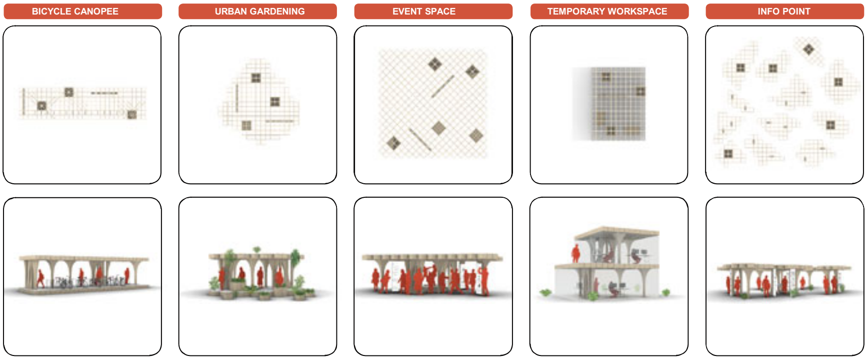


Fig. 1 A modular design approach combined with combinatorial logics enable a range of different geometries and possible user scenarios as demonstrated in the 3DWoodWind research prototype project (see Sect. 4.2)

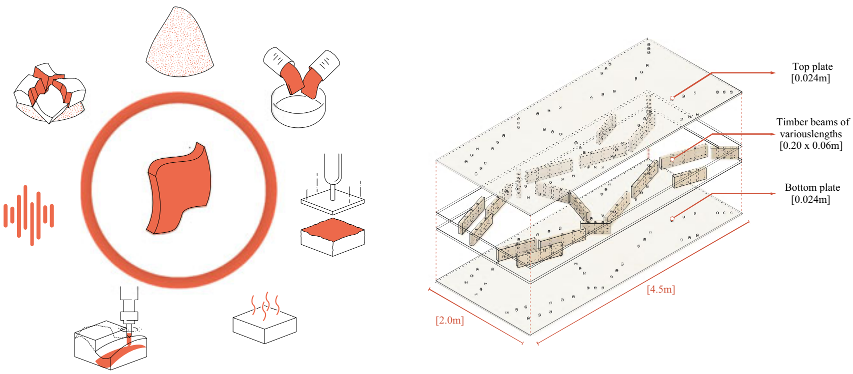


Fig. 2 Left: Circular material process: construction methods using compressed waste-wood particles in combination with bio binders. The material can be shredded and reused multiple times in the same process. Right: Robotic assembly and adhesive-free joining of beams and plates for material-efficient building components, that can be easily recycled

Material Distribution. Current approaches to the use of sustainable materials in construction are often based on solid building components, such as clay, bio-bricks or cross-laminated timber constructions. If the goal is to increase the scope and quantity of renewable resources, it is therefore necessary to develop methods for more efficient use. Computational design tools and digital fabrication technologies offer an alternative, enabling the development of processes for efficient material distribution under different load and support conditions. Furthermore, they also enable to account for the combination of materials of different grades, embedding the unique characteristics of each material as parameters. We propose various computational methods and adapt them to the specific requirements of design with sustainable materials and reversible joining techniques. This includes (see also Fig. 3):

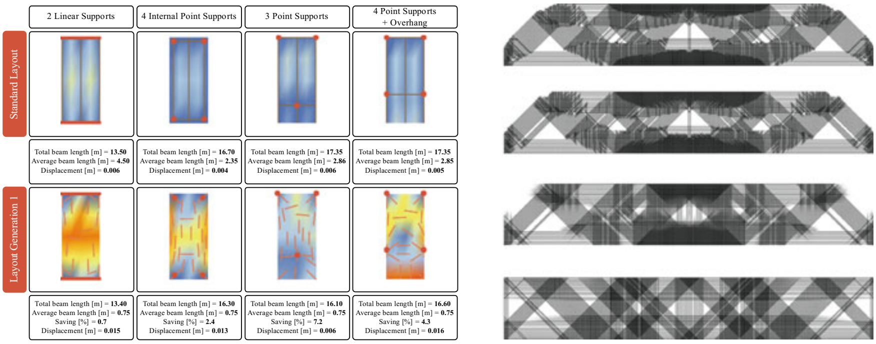


Fig. 3 Left: Distribution of timber beams in a robotically assembled hollow slab component based on stress-lines tracing (see Sect. 4.1). Right: Distribution of willow filaments in a beam manufactured through robotic additive manufacturing based on topology optimisation (see Sect. 4.3)

- Tracing principal stress lines on slab components with the aim of locating and orienting support beams in the areas where higher stresses occur.
- Topology optimization [85, 86], for which we developed a variety of discretization processes of the continuous material distribution obtained through a TO method [87]. Various applications of such method include the placement of beams in slab components, as well as the placement and orientation of timber fibers in our custom AM process.
- Shape optimization, through physical simulation and real-time stress material stress analysis, as we showed in a study on cold bending of glass [88].

These methods offer a flexible matrix of strategies to define an efficient material distribution. To this regard, one of the goals of our research is also to redefine the concept of material efficiency itself, going beyond the exclusive usage of material amount as the dominant metric, and rather attempt to also include material dimensions and grading, as well as the possibilities of reusing existing stocks of waste material from other sources rather than primary ones. Redefining material efficiency in this way allows for a more open and flexible design workflow, able to account for the unique characteristics of architectural construction (see Fig. 4).

Design for Robotic Fabrication. Using the above-mentioned computational methods for material distribution often results in very complex and irregular geometries, making conventional production processes highly inefficient for manufacturing. For this reason, we propose the use of robotic arms as flexible fabrication platforms, able to perform a variety of tasks within a single process. However, this requires designers to account for the unique characteristics and limitations of industrial robot arms already in the design phase, to ensure the buildability of the generated structures. Our approach relies on the definition of any fabrication process as first step in the development of a new design and production workflow. Using computational design tools, it then becomes possible to embed the limitations of the developed fabrication

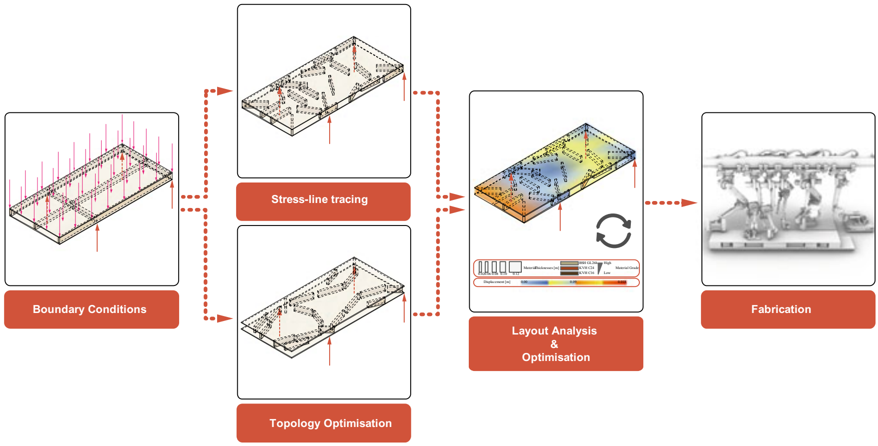


Fig. 4 Overall diagram of a continuous workflow of a hollow-core beam and plate system with form-fit, adhesive-free joining, linking together material layout generation, layout analysis & optimization, material sizing, grading and robotic assembly

process already within the design tools, hence enabling fabricability while generating the design itself. Moreover, having already determined the requirements for fabrication also means that design models can embed all information required for fabrication, which can be regenerated for each design iteration parametrically. One of the limitations to be addressed is the scale of fabrication and transportation equipment. Such limitations come to define the main manufacturing constraints, which in turn determine the maximum allowable size of a building component. Thinking in systems rather than in monolithic structures, these dimensions form the base for the development of individual elements, which can be further combined in modular building components fitting within an overall construction system.

3.2 *Robotic Fabrication Methods*

The use of robots for additive processes can be largely categorized in:

– Discontinuous Assembly: Pick-and Place processes
– Continuous Assembly: Additive Manufacturing.

For a successful implementation of these methods, an adaptive robotic setup, modular open-source tools, and automated material joining methods are required.

Adaptive robotic setup. In the framework of a DFG major research instrumentation grant, we developed a research facility for Robotic Architectural Production (RAP-Lab), which enables a wide range of architectural, building construction and materials

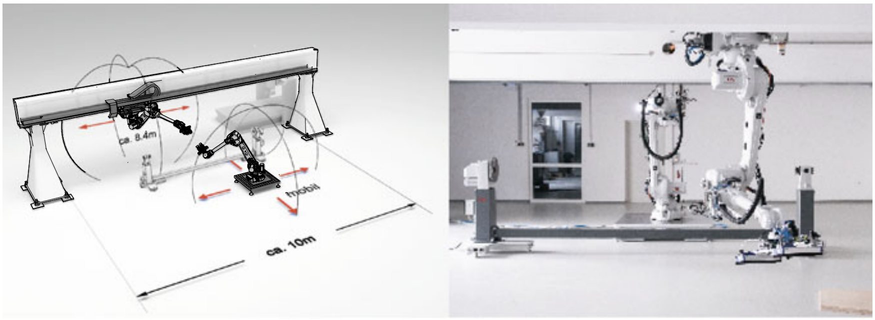
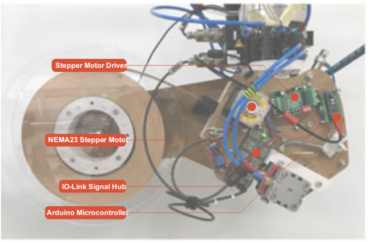


Fig. 5 Robotic Architecture production lab, experimental and digital construction, University of Kassel

science research projects. A suspended ABB IRC 4600 industrial robot on a TMO-2 Güdel gantry was combined with an ABB IRBPL rotational axis, and a mobile, same-sized robot that can be moved and used in cooperative workflows. The system is designed for maximum flexibility through the possibility to run the robots and axis in multiple combinations separately or as a real-time synchronized, 14-axis multi-move system. For tool control, Baluff Profinet IO-Link hubs and digitally configurable pneumatic valves from Festo are integrated on each of the robots, so that only a small amount of additional wiring is required and changes in the control structure can be made via software. The tools themselves are seen as modular functional entities within different control layers. This means that i.e., a tool or tool-system is not integrated in the main controller, but has all the functionality and data collection integrated, so it can be actuated by different robots with simple means. Since the lab is mainly used for research purposes, the entire robot hall was defined as a safety zone. Four mobile three-level enabling safe-switches allow several people to operate the robots in collaborative processes. Even though the facility is unique in its design, adaptability, security and control methods, we used only standard equipment, therefore enabling simple transmission and adaption by industry (Fig. 5).

Modular open-source tool ecosystem. Integrating our various manufacturing processes requires a flexible approach to both robot programming and end effector control. Previously described existing approaches rely either on a centralized approach, where a single tool attempts to address all issues, often resulting in low flexibility, or on the custom combination of separate tools, which needs to be redeveloped for each project, resulting in low transferability of the results. Borrowing the metaphor of the “cathedral vs. bazaar” of Raymond [89], we propose an approach which combines software and hardware elements of a robotic fabrication process through a series of shared interfaces, without imposing a fixed workflow [83]. This is achieved through an approach combining tool components fabrication using low-cost FDM 3d printing and readily available electronic components, with a software interface able to integrate and control such elements in a coherent workflow, and to allow their communication with the robot control code.



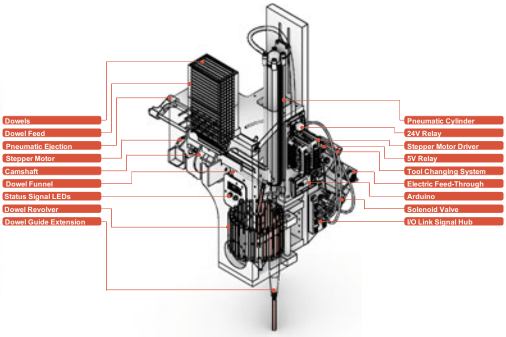


Fig. 6 Modular robotic endeffector examples. Left: Winding tool integrating a stepper driver and its motor, an Arduino microcontroller, and an IO-Link hub interfacing the signals with the robots ProfiNET network. Right: Doweling tool with various components for dowels loading, alignment and press-fitting through a pneumatic piston. A series of motors guide the dowels from the magazine to the insertion position, and sensors track the process

To achieve such goal, we developed two separate open-source tools:

- Robot Components [90], an intuitive robot programming and simulation framework for the Grasshopper visual programming environment, which enables to easily transform CAD geometry in robot instructions for ABB robots.
- Funken [91], a serial communication interface for the Arduino framework, which allows the programming and actuation of electronic components from various computational design and creative coding tools, such as Grasshopper, Python, Processing and NodeJS.

Together, these two tools, combined with our modular and open approach to tool design and manufacturing (see Fig. 6), enable the level of flexibility and adaptability necessary to the unique needs of research in architectural fabrication.

Automated Material Joining. Both for discontinuous and continuous fabrication processes, methods for joining materials are required. The joining technologies and materials also have a large impact on sustainability, since they determine the reusability and recyclability of the components. It is necessary to investigate the specific sustainability requirements according to the base material choice, and to evaluate the performance requirements (structural, building physics, acoustic), to determine the feasibility of natural binding methods. Wherever these requirements allow for it, natural binding methods should be used with bio-based adhesives or even adhesive-free methods as form-fit connections or bio-welding (see Fig. 7). Form-fit connections are created through shaping the material in ways that it can be interlocked in direction of the applied forces. This can be achieved through CNC milling [84], laser-cutting [34] or 3d printing [92]. Also, higher-grade material can be used only for the joining part, as for dowels [93] and other forms of interlocking joining [94]. It is also possible to design the whole component in a way that it topologically interlocks with the neighboring ones [95]. Bio-based adhesives can be based on starch, lignin,

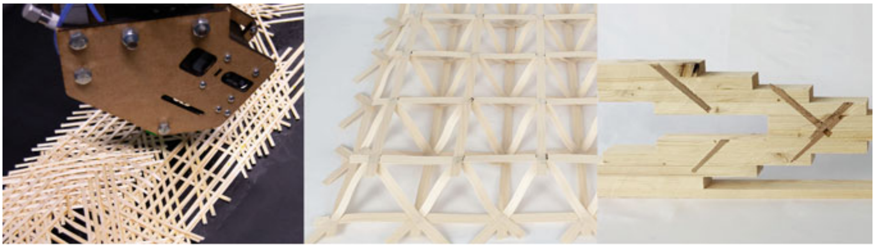


Fig. 7 Left: Robotic willow filament placement process. The use of bio-based binders is possible for non-structural applications. Middle: 3D lattice of maple veneer for integration with mycelium as a bio composite. The joints are realized adhesive-free, through ultra-sonic welding. Right: Robotic press-fitting of beech wood dowels, section cut

tannin, proteins and chitin, among others [96]. We experimented with protein and glutin-based adhesives in additive manufacturing with solid willow filaments (see Sect. 4.3). We have also been investigating starch and protein for binding wood particles (see Sect. 4.5) [97], as well as chitin-based foils to laminate timber filaments. It must be noted that they have not yet been reaching similar performance levels as synthetic ones, particularly concerning structural capacity, humidity and temperature resistance. Material inherent binding agents can also be activated, as lignin in wood, as research on friction welding of timber shows [98]. We recently started investigating ultra-sonic welding of thin veneer filaments with promising results (see Sect. 4.4) [100]. For high-performance components as for structural use, chemical binders might still be necessary. Here, a strategy can be to apply these adhesives, in analogy to 3d printing, only where there are actually necessary in digitally controlled precise amounts (see Sect. 4.2).

4 Case-Studies

Five case studies exemplify the previously described methods at different scales, ranging from the robotic assembly of entire structural slab components to additive manufacturing with wood filaments to investigations on new materials based on wood fibres and biogrowth. The studies are described through the employed materials, computational design approaches, robotic fabrication processes and tooling.

4.1 Assembly and Joining Methods for Modular Timber Components

This project researches computational design and integrated structural joining methods for robotic assembly in timber construction. The focus was on planar surface

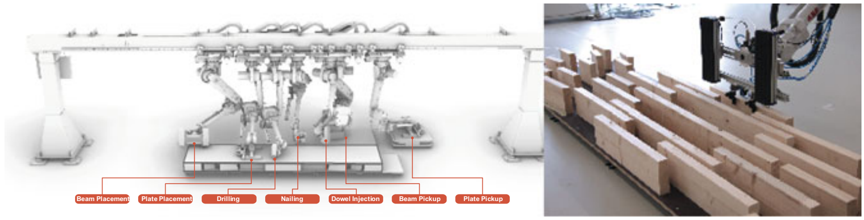


Fig. 8 Left: Diagrammatic perspective view of the robotic fabrication setup showing the individual steps of the assembly process: Pick and place procedure of the beams, laying the top plate without any fixation, nailing the plates for fixation, drilling, injecting dowels. Right: Image of pick and place procedure of the beams

elements, the most common typology of building component used in architecture, as floor and wall elements, often requiring adapting to variable supports and loads. We investigated a novel connection system with robotically placed wood nails and dowels, adapted to force direction. As materials, we used standard solid wood beams of variable dimensions, OSB Wood strand plates, beech wood dowels and nails. We investigated computational optimization approaches (tracing principal stress lines, topology optimization and sizing) in combination with multi material optimization (different timber grades and materials (softwood, beech) (Fig. 3), to optimize for goals as the reduction of the total material volume, reduction of the total costs of the structure, by using lower grade timber where possible and reduction of the global warming potential (GWP) of the used materials [99].

Robotic fabrication was structured as a “pick and place” process (see Fig. 8). Since the joining is effectuated through wood nailing and dowelling, no additional chemical adhesives are required. In terms of automation, we integrated pneumatic two-finger grippers for beam assembly and surface vacuum grippers for handling plate elements. For assembly fixation, we used a manual wood nail-gun, which we automated through pneumatic control. For automated dowel insertion, we developed a custom tool with 3d printed components for material stock, loading through stepper motors and a pneumatic piston for automated dowel insertion (Fig. 6). The dowels were pre-dried for simpler insertion.

By using a layered system of wood plates and short beams, the system is continuously extendable, and it was possible to break away from the reliance on non-reversible gluing processes, as well as to potentially allow the reuse of material from construction demolition, the use of offcuts from production or even to differentiate material grades depending on specific project requirements.

4.2 Robotic Winding of Hollow-Core Timber Elements

Winding technologies are commonly used for the manufacturing of highly resistant lightweight synthetic fiber composites. Our research investigated new potentials for lightweight, material-efficient construction with timber through robotic winding of thin continuous timber strips, providing intact, continuous, and tensile natural fibers. Linear and freeform components with varying cross-sections can be created, as architectural and structural components in construction: furniture and industrial design objects, columns, beams, floor slabs or façade components. The material system is composed of locally sourced hard- and softwood-based veneers strips of only 0.5 mm thickness and certified moisture-curing polyurethane adhesives for structural applications.

We developed both NURBS and mesh-based winding-line generation methods which minimize buckling or twisting of the filaments using locally-geodesic curves [101]. Through computational control of the winding layout, surface geometry and winding sequence, the material can be optimally distributed and customization possibilities as variable patterns with open and closed surfaces and braiding effects can be achieved. The structural filament layout optimization is currently investigated through FE-modeling.

Different robotic setups were used during the development of the project. Initially, the winding process was prototyped on a small robotic arm with a custom-developed rotational axis, controlled via Arduino. For further development, we used a 4 m long horizontal winding axis, which was integrated with the robot controller for precise synchronous movements. The winding tool integrates pneumatic devices for filament cutting, stepper motors for extrusion and an automated adhesive application system (Fig. 6). The proposed robotic framework enabled to switch between the different setups with minimal changes to the design and programming setup, allowing to adapt the production process to the different fabrication equipment available in different stages (Fig. 9).

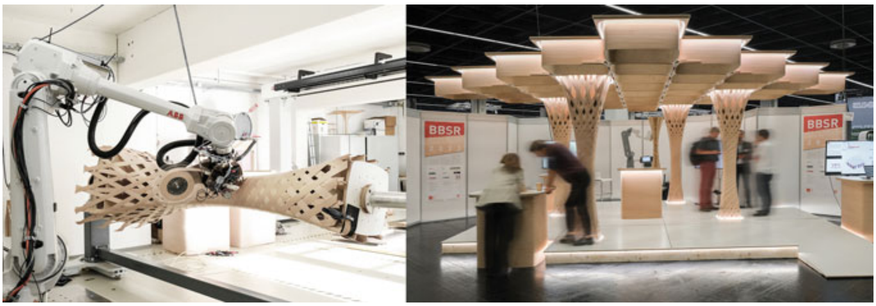


Fig. 9 The 3DWoodWind project uses strips of thin veneers to and industrial robots to wind structural components as columns and modular ceiling components for full-scale architectural structures. Right: The BBSR Research Prototype was presented at the Digitalbau 2022 in Cologne

4.3 Additive Manufacturing with Solid Timber Filament

In timber construction, currently few large-scale 3D-printing methods exist. Present processes use wood in pulverized form, losing material-inherent structural and mechanical properties. This research proposes a new material, which maintains a complete wood structure with continuous and strong fibers, and which can be fabricated from fast-growing locally harvested plants [102]. We investigated binding and robotic additive manufacturing methods for flat, curved, lamination and hollow layering geometric typologies, and characterized the resulting willow filament and composite material for structural capacity and fabrication constraints [103]. As materials, we used willow filament, developed within the project FLIGNUM at Uni Kassel [10].

To be able to design while keeping material and manufacturing constraints in mind, as the maximum overhang angle, heights, and minimal radii, we created computational design methods that integrate and control resulting geometries for fabricability directly [104]. We also investigated a high-resolution material distribution through topology optimization (Fig. 3) constrained to the dimensions and linearity of the willow filament [23].

The robotic fabrication is characterized as a continuous process of material application, apart from cutting the wood filament when other direction lines are applied. For joining we investigated a range of chemical adhesives, as contact adhesives, uv curing adhesives, and PU hotmelt adhesives. We also investigated natural adhesives as Glutinglue, Kasein, and Chitosan. Automation of the process is performed by stepper motors for extrusion, pneumatic devices for cutting the filament, adhesive application through extrusion, and an automated UV curing LED system (Fig. 10).

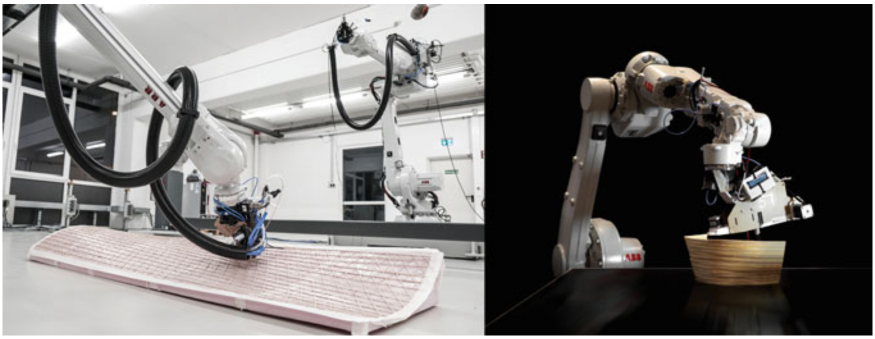


Fig. 10 Additive Manufacturing with a new material: a solid, endless filament made of split willows, an extremely fast-growing plant that can be harvested in Europe. Bio-based adhesives were investigated

4.4 Biofabrication with Timber Reinforced Mycelium

In this research project, a wood-mycelium composite construction method for CO_2-neutral, circular interior systems was investigated. Since mycelium has a low load-bearing capacity, reinforcement and 3D lattices were developed via additive manufacturing techniques from local wood species, which serve as a matrix for biogrowth. This allows to increase the scale of mycelium-based components from the available acoustic panels [21] to a wood-reinforced interior building system, while keeping the 100% bio-based, compostable material qualities. We used Ganoderma lucidum and hemp hurds for mycelial growth and maple veneer for reinforcement. [105].

Design rules for 2d and 3d wood lattice structures were developed both for structural efficiency and fabrication constraints. Initial tests were performed using 2-dimensional flat grids of veneer placed on the outer surfaces of the mycelium components. While this slightly increased bending resistance, it resulted in shear failures within the material. Hence, a novel 3-dimensional grid was developed, where the two flat grids on the outer surface are connected with veneer stripes through the material cross-section, providing the required shear resistance to the final panel [105].

A continuous robotic fabrication process was employed for laying the veneer strips, using extruders, pneumatic cutting devices and robot motion for the placement. For adhesive-free-joining of the veneer layers, we developed an ultrasonic welding method (Fig. 6). Thereby, the wood inherent lignin is performing the material joining [100]. The bio-growth process must be precisely controlled and has to go through the following steps: Substrate inoculation (collection, sterilization of hemp hurds, inoculation with G. lucidium grain spawn, 2 weeks in incubation room with temperature and humidity control); Molding (3D lattice of maple veneer is filled with mycelium substrate, 3–6 days in incubation room), demolding (Fig. 11).

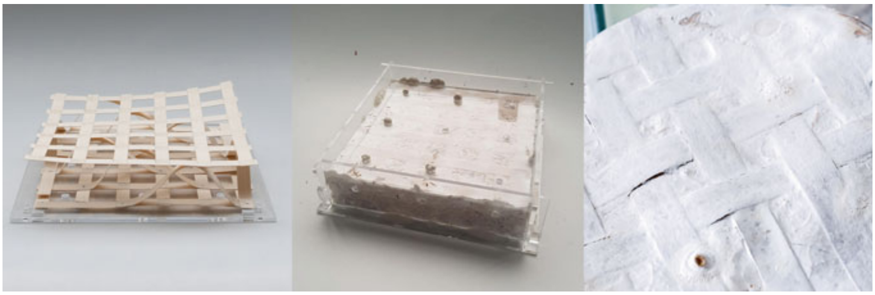


Fig. 11 The HOME project investigated the combination of additively manufactured timber 3d lattices in combination with bio-growth of mycelium, producing a novel reinforced biomaterial, that is fully compostable

Fig. 12 Left: Compacted and milled acoustic elements from used wood particles and starch. Right: Investigations in a 3D-printable, 100% bio-based wood paste

4.5 AM—Compression and Reuse with Wood Particles

The aim of this current research project is to reuse waste wood in a zero-waste process to produce components with a high degree of curvature, for use as lightweight, fireproof and precisely manufactured insulation and acoustic elements, enabling a complete circular material cycle (see Fig. 2). Applications for interior, model and furniture construction as well as concrete formwork are also conceivable. The waste wood is completely recycled and reshaped in the form of wood chips with the addition of sustainable biogenic types of binding agents and with the help of digital manufacturing processes and transferred to new circular construction applications with a requirement for complex geometries. For this we investigated the use of starch, animal and plant-based proteins, and chitosan binders, which are biogenic and result from industrial waste flows.

At the end of the life cycle, the particle-based components and the wood chips from the shaping process can be recycled and reused, creating a closed material cycle. Also, additive manufacturing processes are investigated through the development of an extrudable wood paste (see Fig. 12). The material has a promising compressive strength, enabling a possible substitution for concrete printing in the future. For preliminary investigations, we automated a manual clay extruding device, and added 3d printing parts for material storage and actuation.

Computational design methods are being developed for the surface pattern and acoustic design in conjunction with digital fabrication constraints.

5 Conclusion

This article addresses developments needed in the construction industry to reduce CO_2 emissions and enable strategies to achieve the goal of "more with less" through circular design approaches and lightweight, material-efficient structures using sustainable materials. We provide an assessment and review of current research, automation technologies and practice, to place our research in the context of industry 4.0. Integrative design and manufacturing approaches are needed that simultaneously provide holistic, circular design approaches and fully exploit the advanced geometric capabilities of robotic manufacturing for material efficient components. Digital design methods not only provide the data for their constraints, but also enable a direct and seamless workflow between design and manufacturing. Towards these goals, our research provides computational methods, material development, and robotic automation technologies.

We proposed combinatorial logics in conjunction with modular components that can be functionally expressive and highly optimised to enable component reuse for different application scenarios. Through computational tools, we are able to combine optimisation technologies for material efficiency with the constraints of robotic manufacturing.

This is demonstrated through five case studies in different scales, ranging from the robotic assembly of entire structural slab components to additive manufacturing with wood filaments to investigations on new materials based on wood fibres and biogrowth. The studies were distinguished through the used materials, computational design approaches, robotic fabrication processes and tooling. The difference in size of the employed materials thereby determines the possible resolution of assembling and has an impact on the application scenarios of these technologies. The additive nature of the described systems allows for continuous extensions in multiple directions, allowing for a maximum of design freedom and functional use through geometric variability. These studies show that not only the materials, but also the joining methods have an impact on the sustainable potentials.

We showed that timber beams and plates can be connected through form-fit wood-wood joint methods in automated processes. Therefore, after their service life, no material separation is necessary, making the components easily recyclable. We presented methods for material-efficient, hollow, lightweight components through 3d winding of timber in combination with adhesives. Since certified bio-based adhesives for structural applications are not yet available, we developed a highly precise digital application system, which minimizing adhesive use. An alternative to timber is fast-growing willow plants, that we used to produce an endless solid filament. We investigated novel robotic additive manufacturing processes with bio-based joining, that can be used for semi-structural applications and interior fittings and furniture. Our research on mycelium-wood composites shows that biomaterials that are reusable and fully compostable after their end of life could be used in large-scale applications in architecture. The rethinking wood project starts already a step further in a circular process in taking as base material timber particles from waste wood. The bio-binding process allows also to repeat the process several times from waste of components derived from this method.

Furthermore, tackling the challenge of lowering the access threshold to the adoption of such technologies in construction, our research demonstrates the development and application of open-source tools for the programming of industrial robots, as well as for the actuation and orchestration of the various hardware and software components involved in the production. By providing the tools as open-source packages, as well as developing more accessible and intuitive software and hardware approaches to robotic fabrication, we aim to extend the range of applicability of such technologies to a broader audience of designers, construction firms and other stakeholders in the domains of architectural design and fabrication.

Combined, these proposed approaches aim at providing a model for integrated design and fabrication of sustainable and efficient building components for architecture, providing an effective alternative to conventional design and production processes.

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