ABSTRACT
Platforms that integrate developments from multiple disciplines are becoming increasingly relevant as the complexity of different technologies increases day by day. In this context, this paper describes an integrative approach for the development of architectural projects. It portrays the benefits of applying such an approach by describing its implementation throughout the development and execution of a building demonstrator. Through increasing the agility and extending the scope of existing computational tools, multiple collaborators were empowered to generate innovative solutions across the different phases of the project’s cycle. For this purpose, novel solutions for planar segmented wood shells are showcased at different levels. First, it is demonstrated how the application of a sophisticated hollow-cassette building system allowed the optimization of material use, production time, and mounting logistics due to the modulation of the parameters of each construction element. Second, the paper discusses how the articulation of that complexity was crucial when negotiating between multiple professions, interacting with different contractors, and complying with corresponding norms. Finally, the innovative architectural features of the resulting building are described, and the accomplishments are benchmarked through comparison with typological predecessor.
INTRODUCTION

Technological changes are advancing simultaneously in numerous fields, but to truly innovate and build better architecture, those advancements need to inform and affect each other. Different disciplines unfold their expertise at different phases throughout the process of producing a building. Thus, to enable a synergistic relationship between them, the classical project chain defined by the Royal Institute of British Architect as “Concept Design, Developed Design, Technical Design, Construction and Use” needs to be broken up. That change will allow for feedback between the architectural definitions that are usually set at different moments of the project’s development. Naturally, the aim is not to disable the chain completely but to allow for Parallel Development—a well-known strategy in the management of Software Development.

The research presented here will introduce how custom computational tools took interdisciplinary collaboration to a higher level and enabled the integration of several cutting-edge technological developments, where all the specifics and the complexity of each discipline was integrated into a novel building system for segmented timber shells. This work focuses on developing digital modeling tools for a Hollow Cassette System (Krieg 2018) (Figure 6).

The research described here builds up on the results of prior studies (Schwinn 2014; Krieg 2015; Krieg 2018; Groenewolt 2017) and was based on developing methods for managing the coordination across architectural design, engineering, fabrication, and assembly. The advancements presented focus on the integration of those fields when going from Development Design to Construction of the Building Demonstrator described later in this paper. Above all, it is crucial to remark that the approach and developments introduced here need to be differentiated from works where computational tools and digital fabrication are deployed after concept stage. Rather we seek to reformulate how the technological advancements and computational tools relate to the process of designing buildings.

BACKGROUND

Architectural Context

Thin double-curved shells have been employed in many architectural examples throughout the last century. The way of producing such formal complexity often relied on the use of reinforced concrete shells, for which an large amount of manual labor and material for the formwork was required. This heavy toll may have contributed to the limited proliferation of the typology around the world. However, by bringing together expertise and novel developments in wood engineering, manufacturing technologies, and computational design, double-curved shells can nowadays be constructed from planar curved shells can nowdays be constructed from planar-curved shells can nowdays be constructed from planar wooden elements with minimal scaffolding (Krieg 2015).

Biomimetic Research

The building system for these segmented timber shells is based on the differentiated morphologies that can be found in the skeleton of sand dollars, which are scientifically classified as echinoids. Foregoing the process of working with concepts and pre-conceptions, nature has developed incredibly sophisticated structures through millions of years of trial and error (Wester 2002). The echinoid’s segmented shells are an example of nature’s highly efficient structures, exploiting the variation of their geometry and shapes in order to optimize material and energy use. Within the echinoidea class, sand dollars employ plate structures with interlocking connections between the shell’s individual plates (Figure 2) (Grun 2016). Collaborations with biologists have proven fruitful for the understanding of these structural systems, which enabled an informed transfer of these biological principles into the building scale.

From Solid Plates to Hollow Cassettes

The first project that employed the system of segmented timber shells on an architectural scale is the Landesgartenshau Exhibition Hall built in Schwäbisch Gmünd in 2014 (Figure 3). Solid plates were employed as modular planar elements in a shell that spanned 17x11 m and generated a footprint of 125 m² with only 12 m³ of wood. All 243 modules were defined as computational entities that were aware of their geometrical constraints, material stock sizes, and fabrication parameters (Schwinn 2014).

This award-winning project demonstrated the performance of segmented plate structures, but in-depth structural
analysis revealed that the building system could still be significantly improved (Bechert 2018). By slicing each plate in half and embedding a ring of edge beams, a double layer structural system was conceived. These hollow cassettes easily reach a structural height of 160 mm with the same amount of material per square meter of shell surface, reaching triple the span of a shell structure with solid segments.

Methods: Integrative Interdisciplinary Design
When shifting from a solid plate system to a hollow cassette system, many aspects require further development. An eightfold increase in the amount of parts and their corresponding relationships considerably increases the amount of information required for the modelling of the elements as well as for the corresponding manufacturing processes.

A computational tool based in Rhino’s Grasshopper plug-in was developed with the goal of expanding the scope of digital models to fabrication and construction, giving all involved collaborators the possibility of checking architectural definitions against the final production geometry and construction logistics at any time of the process. Normally, decisions made at a deep level of detail are left to the contractors to define. By connecting these deep-level definitions with other aspects, and making them part of an integrative design process, concerted adjustments can be made without making the process more laborious. This increases efficiency, speeds up design development and analysis and enables the use of solutions that would not be feasible otherwise.

The digital interface was built upon developments from previous projects, such as the use of interactive agent-based modeling methods (Groenewolt 2017) and computational analysis of material efficiency, environmental impact, and economic aspects of the building system (Krieg 2018). Previously developed C# object-oriented programming classes were extended to enable the computation of information concerning connection details, to generate machine code for multi-robot fabrication, and to include the assembly logistics for a building system with a higher complexity. Usually, different aspects and properties of each architectural element are described amongst different sets of drawings (such as architectural drawings, structural documents, and fabrication drawings) made by various professionals. BIM interfaces already digitize these drawing sets and accumulate them in digital models. Nevertheless, they are often still used in ways that mimic conventional methods: even when models are shared between project partners during the design phase, drawings are the documents used to produce a building. The expertise of contractors and constraints resulting from manufacturing methods are unfortunately rarely—if at all—integrated in BIM models, which can lead to a loss of efficiency and may lead to having to redesign and engineer building parts multiple times.

The benefits of the computational tools developed for this project were tested and validated by their deployment throughout the full design and production cycle of the building demonstrator, including negotiating between multiple professionals, interacting with various contractors, and complying with the corresponding norms.

In the process described in sections 3.1 to 3.6, each object representing a building component (cassette) of the shell structure accumulated different types of information. Throughout the entire process, the different properties of its shape were constantly negotiated against all the information related to its production processes, as well as their interacting neighbors; in modular structures, the...
The shape of the elements is as important as the interfaces between them. Each cassette object is represented by a computational agent that includes different categories of information: (a) geometric parameters, (b) the topological relationship with its neighbors, (c) the final shape of its elements used for machining, (d) the shape of its elements in their different production phases, (e) static properties, (f) material properties, (g) environmental and life-cycle data, (h) connection hardware and installation constraints, (i) fabrication data related to the robotic fabrication of the components, and (j) information about the logistics throughout the whole process.

The management of the information was centralized and managed by the architectural core team composed of architects and engineers. The data amongst them was exchanged directly as raw data almost continuously throughout the development phase. The associated fabricators will interact through files containing solid objects with STEP format due to the current industry conventions. Because of that, their contribution to the development of the building system was always mediated by the core team and checked through solid models.

**Architectural Concept**

In early concept briefs for pavilions at the Bundesgartenschau 2019, the clients asked for an open and flexible event space including a stage and space for up to 400 visitors. Based on these functional requirements and the specifics of the site, a design concept was developed. This concept involved a smoothly curved space with three dynamic arches that invite visitors to enter from various directions. The cavities of the shell’s segments provide very good acoustics and the space is well suited for concerts and public events. In order to implement the above-mentioned architectural qualities, structural challenges needed to be addressed from the beginning. To attain open, slender long-span arches, wing-folds at the edges were introduced. This feature cleared the inner shell from increased bending moments and also acted as a prominent architectural feature (Figure 4).

**Segmented Planar Shells**

Agent-based modelling was used in the project to achieve a meaningful planar segmentation of the shell’s global geometry. The use of previously developed methods that combine agent-based methods with interactive design input (Groenewolt 2017) were crucial to negotiate automated segment generation with architectural design intent. The fold at the arches required the generation of different types of panels for the shell, as they feature a different assembly method. The segments directly at the fold line of the arches followed a more constrained, regular arrangement, while the segments of the shell’s apex allowed a self-organization process with more freedom for each agent. The positions of segments in the direct vicinity with the ones at the fold line were partially controlled manually while the remaining agents were actively interacting, in order to create a smooth transition from a rigid grid to a less constrained segment distribution. This differentiated segmentation shows a big variety in shape and scale of the plates, comparable to what can be found in the plate structure of...
the sand dollar (Figure 2). In the sand dollar’s natural shell structure, these different shapes are also the result of differentiated functional requirements.

Hollow Cassette System
As mentioned in the introduction, to minimize material consumption and weight, the building system is based on the developments of previous research (Krieg 2018). Each segment is conceived as a hollow component, constructed from two planar plates separated by a ring of beams (Figure 6). Bottom plates are cut open to generate certain architectural features, reduce weight, and grant access inside the modules for straightforward on-site assembly. The plates and the beams were made of laminated veneer lumber (LVL).

Structural Optimization
The global form of the shell is the result of interdisciplinary work between architects and structural engineers. The global design surface and its associated segmentation are results of an optimization study including both architectural design criteria and structural performance. To achieve this, a broad variety of parametric design iterations was created and analyzed from both perspectives (Figure 7). This led to the selection of a design geometry at an early stage, which was already well informed by constraints resulting from the fabrication process and the shell’s structural performance.

The complete digital workflow from design to fabrication required a compatible process for structural design and analysis. All information relevant to the structural design had to be extracted directly from the digital fabrication model, including geometry information, material thicknesses of plates and beams, fiber orientation of the wood, arrangement of connection elements, and supports. This required a continuous data exchange interface and a parametric structural model, allowing to track design changes and updates resulting from fabrication or assembly constraints, as well as to return structural feedback to the geometry model. As the complexity of the segmented timber shell largely exceeded the pre- and post-processing capabilities of commercial structural design software, customized tools were developed during the project, to assemble the structural design model, visualize results, and properly document them. This integrated approach enabled a design process in which no drawings were needed, apart from the documentation for external institutions and administrative purposes.

Cassette Modulation
Due to the integrative nature of the design process, the main architectural features were imbued with very specific demands from the structural analysis, especially those that were intrinsically related to the modulation of the form of the cassette elements.

The inner surface of the shell features perforations at the lower plate of the cassettes. Initially these perforations had the sole purpose of providing access to the interior of the cassette, thus enabling the insertion of bolts for connection with its neighbors. Already at the first steps of the process, these openings became an architectural feature that needed to adhere to various, partly conflicting demands. Aesthetically, the openings define the interior of the space. Structurally, they also affect the weight and stiffness of the cassettes; a coordination between both demands became critical. As the process advanced, considerations regarding how the shape of the openings affected the assembly of the cassettes became important as well. At this point, knowing the requirements and highlighting them (a function offered by many BIM tools) was simply not enough. To find a solution that satisfies all requirements for each cassette while at the same time producing arrangements that are architecturally convincing would have become a laborious task. Instead, ranges of possibilities were defined from each involved party, so the solution could be computed and negotiated within the system. This prevents collaborators from changing the geometry without accounting for requirements from other disciplines.

Fabrication
For the fabrication of the cassettes (compare Krieg 2018), a novel robotic timber fabrication platform was developed,
aimed at a maximum of flexibility and transportability. The constraints posed by this platform (e.g., maximum cassette size, beam sizes, cassette weight, and glue type) were used in the iterative and integrative negotiation of design parameter domains, in parallel to the detail planning of the structure. While this necessitates tight integration between design, fabrication and structure, it made possible that the fabrication platform, the detail planning, the structural analysis and computation model were all developed in parallel. Within one year from the commissioning of the pavilion, the fabrication platform was conceptualized, tested, assembled, and evaluated through the full fabrication process of the 376 cassettes of the pavilion.

Until the last day before the start of the fabrication, it was possible to make detail changes in the shell’s design without delaying the project’s progress. This was enabled by (a) the direct interface between computational design model and custom simulation and path-planning tools, (b) the early realization of fully digital interfaces with the carpentry processes, and (c) the cooperative overview and definition of fixed and flexible parameters.

The robotic fabrication platform was fully integrated into the carpenter’s environment. Beams and plates of the cassettes are preformatted on standard carpentry CNC machinery in sorted batches. Each element is tagged with a unique ID and placed into input trays next to the robot platform. The two robotic arms then assemble the raw cassettes from beams and plates in a fully automated fashion until the provided material stacks are fully used.

Plates and beams are gripped from the input trays and assembled on a central turntable, where they are glued together and temporarily fixed with beech nails. The assembled cassette is then placed in the glue press. After the pressing cycle, the cassette is placed onto the turntable again and machined to submillimeter precision.

From the CNC preformatting of cassette elements to the surface finishing by the carpenters, workflows were designed to ensure the correct sorting of all stacks of cassettes on site without reshuffling and minimum temporary storage of materials. The robotic assembly processes were designed to fit within the open- and pressing-time windows of the used glue system.

On-site Assembly

Given the tightly fitting finger-jointed connections between cassettes, the assembly sequence needs to be strategically planned in coordination with the contractor. This is especially important, as in certain areas the cassette’s insertion direction (and therefore the assembly order) affects the design of the finger joints. In a similar fashion, the access hole needs to embody different requirements: from a structural point of view, its size needs to adhere to specific maxima while from an assembly point of view, a minimum aperture needs to be sustained. Reconciling these two parameters ensures that all cassettes can withstand their calculated local stress concentrations while the carpenters can insert bolts and place and hold tools through the access cavity. In this case, the computational model reacts with minimum delay to the carpenter’s development and
prototyping results for smooth and fast workflows.

At the level of the waterproofing and the cladding that is mounted on top of the structural cassettes, tight cooperation between contractor, designers and lightning engineer was necessary. From the mounting sequence, the strategy for correct positioning to the design of the fiber direction in each panel, everything depends on the productive cooperation between actors through correct visualization, programming, and communication.

The pavilion was erected in three assembly stages: (a) spine cassettes are pre-assembled into six assemblies of half-arches that are transported to the site and joined to three full arches with a connecting ‘keystone,’ (b) the inner shell is constructed piece by piece following a cantilever method of assembly without scaffolding, starting from the three foot-areas, and (c) the cassettes of the three wings are connected to the open edges of the pavilion.

**RESULTS AND REFLECTION**

Building Demonstrator

The Buga Wood Pavilion 2019 demonstrates the possibilities for efficient, ecological, and expressive wood architecture that can arise at the intersection of digital innovation, master craft, and scientific research. It spans 30 m and covers an area of 500 m², using only 45 m³ of wood. Having a total shell surface area of 600 m², the structural wooden elements weigh 36.02 kg/m². Although this is similar to the 38 kg/m² of the Landesgartenschau Exhibition Hall, the Buga Wood Pavilion 2019 achieves triple the span.

Because of the interdisciplinary and collaborative endeavor enabled by the computational tool here described, various aspects driven by technical demands ended up showcasing remarkable architectural qualities.

First, the plate’s grain direction is driven by structural design to accommodate for the best use of material. That way, a powerful perspective effect when being inside the shell is created (Figure 9).

Second, when walking outside, the direction of the cladding’s grain direction is driven by the direction of the water. Such arrangement ensures the best durability and generates a dynamic effect for the external appearance of the structure (Figure 1).

Third, the cut-outs of the inner plates were initially generated for accessing the internal part of the cassette module, in order to create bolt and screw connections. The cavities formed a perfect space for lighting appliances and provided depth to the shell’s inner surface (Figure 9 and 10). The resulting acoustic performance is perfectly suiting different type of events, such as amplified concerts and talks.

All prefabricated shell segments were assembled in only 10 working days by a team of two craftsmen, without the usually required extensive scaffolding or formwork. Such efficiency was possible by the fine tuning of the building system, in particular the joints. The computational tool processed 376 modules with 1139 cassette edges and the corresponding interrelations between them in terms...
of connections and assembly sequence. A total of 1128 plates with custom grain direction, shape, and thickness were handled. A total of 2168 beams with bespoke geometries were computed, including all necessary connections: 17618 finger joints, 4343 bolts and 952 screws, which all needed to comply with building code and accessibility and assembly constraints.

Additionally, at the level of the connections, the shell is planned and engineered so the building can be fully dismantled and rebuilt elsewhere without losing its designed performance.

CONCLUSION
The project demonstrates that connecting the different collaborators and disciplines and allowing for agile revisions with the option to revise decisions made earlier in the process can be very beneficial for the finalization of all the definitions required to construct a building. By allowing for changes until the last day before the start of the fabrication, significant design improvements could be implemented, negotiating interests and requirements from various partners. These improvements reduced the amount of material needed as well as production times.

Within this setup, two key factors to reach successful collaboration can be identified. Firstly, the establishment of definitions with a clear scope of variation was important, as it allowed multiple disciplines to explore and create their own set of parameters for later negotiation; each discipline needed to find working methods and ways of remaining flexible while going forward at the same time. Secondly, a study that maps the relationship between the different architectural definitions and parameters can improve the process significantly. Going through the complete process from design to completion made clear that different aspects had different levels of influence on each other. On one hand, some decisions tend to be more autonomous, operated mostly in a local manner; these could be optimized almost in relation to themselves only. On the other hand, many other aspects critically affected decisions across different collaborators and remain relevant throughout a large part of the process. Thus, understanding the situation of each of these parameters in terms of their connectivity across different actors and different times of process could make the integration and the negotiations less laborious.

A network that maps the relationships between the parameters across different areas could become a powerful tool for this kind of highly integrative projects, but such a network would be specific to a certain construction method and the necessary knowledge can only be developed through experience. By providing the opportunity to focus on structural, material, and expressive aspects of a design, pavilions that are built in collaboration with industrial partners provide an excellent platform to introduce cutting-edge developments in a context as demanding as the building industry. Nevertheless, the successful collaboration with a timber contractor suggests that the proposed approach has a lot of potential to be applied to actual building construction. These methods could unfold their potential for the building sector even further by subjecting
them to increasingly complex challenges.

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IMAGE CREDITS
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