ABSTRACT
By investigating methods for using computation and digital manufacturing technologies to integrate material properties with architectural design tools, the research in this paper aims at revealing new potentials for the use of wood in architecture. Through an explorative approach, material particularities and fabrication methods are explored and combined into new workflows and architectural expressions. The research looks into different properties and capacities of wood, but the main part of the experimentation revolves around crooked oak logs. Due to their irregularities, these logs are normally discarded. However, through the methods suggested in this research, they are instead matched with unique processing informed by their divergence. The research presents a workflow for handling the discrete shapes of sawlogs in a system that both involve the collecting of material, scanning/digitization, handling of a stockpile, computer analysis, design, and robotic manufacturing. The workflow includes multiple custom-made solutions for handling the complex and different shapes and data of wood logs in a highly digitized machining and fabrication environment. The suggested method is established through investigations of wood as a natural material, studies of the production lines in the current wood industry, and experimentation in our in-house laboratory facilities.

This up-cycling of discarded wood supply establishes a non-standard workflow that utilizes non-standard material stock and leads to a critical articulation of today’s linear material economy. The research thereby gives an example of how the natural forms and properties of sawlogs can be directly used to generate new structures and spatial conditions.
INTRODUCTION
Exploring wood
Wood is an anisotropic material, and the length, directionality, strength, and elasticity of the grains are particular to each species (Hoadley 2000). The research project is investigating the properties and capacities (Delanda 2007) of wood through digital machining methods, metrology, scanning techniques, and hands-on experience. By cutting, splitting, bending, sawing, milling, scanning, x-ray, tomography and printing, a series of experiments illuminate the properties of wood by paying attention to the unique material and processing methods in different ways (see Figure 2+3+4).

The experimentation seeks to let the small-scale behaviors and particularities of wood inform and inspire design potentials, similar to research projects carried out by ICD/ITKE research (Menges, Schwinn, and Krieg 2016) and. Simultaneously, this research project embraces, investigates, and processes the outer geometry of natural wood. This has also previously been explored in the Ratatosk Pavilion by Helen Hard (Stangeland and Kropf 2012), recently at University of Michigan (Von Buelow et al. 2018) and through the immense work produced at Architectural Association Hooke Park (Mollica and Self 2016), where raw wood is scanned and analyzed to forward their properties into informed machining. The experimentation done in this research project involves different types of scanning and various robotic machining processes using a chainsaw, band saw, and spindle, together with bespoke digital analysis and modeling tools (see Figure 1+5).

Crooked potential
In today’s wood and sawmill industry, several actions are taken to optimize tree growth and sawing techniques to maximize the production of straight timber. The industry is highly developed in terms of using advanced technology, such as x-ray scanning, 3D analysis, exterior scanning, and customized sawing (see Figure 6+7+8). However, some high-quality timber still ends up as firewood or pulp due to its non-standard shape. Especially harder, and valuable, wood species like beech and oak grows into crooked shapes that do not fit with the current market and industry standards. Directly inspired by this phenomenon and the present technology in the industry, we suggest up-cycling of discarded timber through alternative use of already present technology. By using scanning and analysis technology similar to what is being used in modern sawmills, the naturally grown shape of the material itself can be used to inform the machining. Likewise, the shapes can be organized parametrically into constructions or building elements. Combined, this has the potential of creating
workflows where the properties of the natural wood inform both the architecture, as well as the creation and of the architecture

Architectural investigations

The processing of wood in its natural form presents (at least) two challenges: one is a technical challenge, and the second is an architectural challenge. The first challenge is quite tangible and consists of the techniques and methods needed to handle non-uniform material back and forth between digital and physical space. The second challenge is the more abstract task of investigating and describing the architectural potential and relevance of utilizing crooked wood in constructions. The two challenges are confronted simultaneously by establishing a series of experiments investigating different types of architectural elements: roof, wall, column, and cladding (see Figure 9). Each experiment type takes its departure in crooked logs but develops different workflows and strategies for computational analysis, modeling and machining. Combined, the experiments can start to form an architectural language that includes the natural form and the aesthetic value of the original wood.

This paper focuses on the considerations conducted for the roof experiment. For this purpose, a system based on the lamella roof principle is investigated. The principle allows the construction of large spans using relatively small wood members. Previous research on the lamella roof principle demonstrates workflows that integrate
computational design and robotic fabrication (Tamke, Riiber, and Jungjohann 2010) However; these projects make use of standardized timber rather than wood in its natural shape.

Using wood in construction, in general, have a positive impact on the carbon dioxide emission level. By enabling carbon sequestration and replacing building materials with higher levels of carbon dioxide emission (Laturi, Mikkola, and Uusivuori 2008; Gustavsson et al. 2006) with wooden building elements the relevance of using non-uniform wood in architectural construction is not limited to the geometrical and tactile potentials. The research also becomes a part of a sustainable discourse where material particularities are applied to specialized uses instead of wasted or down-cycled.

METHOD

The series of experiments in this research have created different workflows. The below workflow description follows the method created in the lamella roof investigation. This experiment represents the most well-developed and specialized workflow but also indicates a general strategy for processing of non-uniform saw logs. The workflow is based on local resource arrangements and available fabrication facilities but attempts to include scalability and methods that could be relevant in a more industrial context by establishing a completely integrated design-to-production workflow. This is done using bespoke computational design tools and digital technology for analysis and fabrication.

The method described below makes use of a Faro laser scanner, an OptiTrack motion tracking system, analysis, and form generation based on Rhinoceros/Grasshopper with Python and Volvox, together with custom made algorithms and plugins. Machining is done with an ABB 6-axis robot arm mounted with, at different times, a bandsaw and a spindle, programmed using the Axis plug-in for Grasshopper.

The saw logs used for this experiment is oak sourced from a local sawmill. The oak is both branches and trunks that are too crooked for use. Straight oak is being used for furniture or flooring; semi-curved pieces utilized in making of more rustic furniture and other arts and craft interiors. The crooked, irregular or unhandy pieces are normally sold cheaply as firewood. This is the wood we utilize in this project.

The handling of the oak logs can be described through three phases; stockpile, design, and fabrication.
photogrammetry and Faro Focus lidar scanner. For larger quantities, the Focus lidar solution has proven most efficient (see Figure 12). Scan data could also be obtained using drones or existing scanning solutions used by the industry.

The scan data is processed into individual point clouds for each log. The reference sticks in each log are identified using an RGB filter and extracted as features. Each point cloud is analyzed using a custom script, and a lightweight NURBS representation of the log is created (see Figure 13). A dataset consisting of a point cloud, NURBS surface, reference points, and labeling is created for each log. The datasets now become a digital stockpile of the available logs. The digital representations can be used in a generative design process where the particularities of the digitized logs are taken into account in a computational negotiation with the overall design and properties of the individual building components.

The stockpile functions as an amassing of resources that can dynamically shrink or grow. At any time, the digital stockpile can be reached, and available resources assigned to a design.

Design
Since the research is grounded in the natural properties of wood, both the knowledge on internal structural principles and the outer shapes are ideally reflected in the design choices. Consequently, this specific experiment seeks at maximizing unbroken fiber directionality and curviness of the logs and thereby maintaining both natural strength and mode of expression. The fitting of the logs into a larger constellation must, therefore, be a negotiation between the available stock material and architectural design intent (see Figure 14).

The overall geometry of the design is defined as a NURBS surface, which then serves as a reference for the following distribution of the logs. The surface is used as base geometry for the algorithmic generation of lamella roof topology, distribution of the logs, the definition of component geometry and fabrication information, i.e., toolpaths for robotic milling or bandsaw cutting. The digital form generation is established as a Grasshopper/Rhinoceros definition with a series of custom written Python modules.

The first step of the algorithm is to subdivide the control surface according to preselected dimensions. The resulting isocurves are divided into curve segments, each defining...
a structural member in the lamella roof system. The next step is to pair each member with a suitable log from the pile. For each individual member, the curvature of the segment is compared with the available stockpile, and the log with a center curve that deviates least from the isocurve is selected. The digital representation of the log is placed on the surface and rotated to match the surface segment optimally. From the control surface, normal directions and tangencies at endpoints is extracted. The orientation of the cuts is defined by the normal vectors of the control surface at segment endpoints. This information is combined with the original center curve of the log and used to define one or more ruled surfaces that describes how the log is to be trimmed or divided lengthwise to fit with the size and orientation of the structural member. The final step is to use this geometric information to generate the toolpaths for processing the component as described below.

The result is a structure where the available stock matches the overall design as closely as possible, while the logs maintain their original curvature (see Figure 15). The algorithm produces a virtual model consisting of components produced from the available stockpile, rather than an abstract model of ideal components. In this way, the resulting design represents a negotiation between design intent and the shapes of the natural materials. A design process can be imagined where the architect tries out a series of configurations with the various number of components and surface geometries, using the algorithmic method to decide on the best compromise between overall design, topology, and available stock material. The workflow in the setup shown here use a stock of logs of approximately same size and matches these with curve segments that also have limited variation in length. However, the system could be developed to locate log partitions within longer saw logs or even living trees and match these with construction members that also display larger variation than in the lamella roof construction.

**Fabrication**

The designs explored in this experiment consists of three fabrication steps: sawing/trimming, joint milling, and assembly. All three steps require different types of matching of digital data and physical material according to the chosen design.

Depending on design choice, the logs are either split or trimmed. In both cases, the centerline of the actual log defines the machining to preserve the original shape. The machining includes a rotation or transformation towards the ends of each log that ensure a better fit with the intended final surface geometry without overruling the
A deeply integrated workflow allows exact machining of crooked logs; shown here is a board cut to precisely follow the grains of the wood, the result of which is a curved and very strong board.

A test for a sub-component of a larger structure; half logs are joined together using dowels.

A solution for joining trimmed logs; a combination of mortise, tenons, and dowels are easy to fit and create a strong joint.
original shape. The sawing and trimming are done on a 6-axis robotic arm either mounted with a custom build bandsaw or a spindle with a custom made milling tool that allows easy machining of the raw logs (see Figure 16).

The robot setup provides high freedom, precise control of the machined surfaces and is deeply integrated with the design (see Figure 17). The toolpath and robot code is generated directly from the digital geometry and pairs uniquely with each sawlog. Just before the robot code is executed, the actual oak log is brought into a position that respects the robot setup’s machining limits. The robot cell is equipped with an OptiTrack motion capture setup that is used to determine the position of the logs by probing and matching of the reference features both found in the digital dataset and on the actual logs. The probing is a lightweight method that allows fast localization of the logs and instant 3D reorientation of the tool paths: A custom made Grasshopper plugin allows direct fetching of planes from the Optitrack system. As soon as the reference planes are available, the robot targets are reoriented within their work-object to match reality (see Figure 19).

The sawing/trimming is followed by a joint milling process. Each log is machined to have joint details in the ends and on the sides (see Figure 18+20). The orientation and position of the connections are created in accordance with the chosen design. The toolpaths for milling of the joints are, again, automatically generated from the digital representation of the log. In the cases of split logs, the warping caused by the stress releases in the wood will often cause the need for a new location and reorientation of the pieces and associated toolpaths. This is again done with the OptiTrack motion capture setup. The assembly is done at the fabrication facilities but could just as well be done at another location.

FUTURE INDUSTRIAL IMPLEMENTATION
The workflow explained in this paper is developed and refined in a lab environment. The stockpile of scanned oak logs is limited to a smaller portion, and many logs are used for basic experimentation and equipment calibration, leaving only a reduced amount of scanned wood to be available for the actual surface matching. The scenario is not ideal but exemplifies the scope of the research. If the research is to be seen in a larger context and a more industrial framework, the potentials of upscaling must be addressed. To approach the industry directly, the research team of this project visited the Finish wood industry and experienced most of the processes behind the scenes. Therefore, most of the steps and methods used in the research workflow are either almost identical or strongly resembles methods actively used in today’s sawmill and wood processing industry. Modern sawmills, for example, make use of advanced laser and x-ray scanning for each individual log. The scanned data is then used to categorize the logs and plan efficient sawing methods. Or to discard logs that do not meet the standards, e.g., if they are too crooked. This also means that each log, including each discarded log, has a 3D surface, and often also interior scan data, attached. An obvious potential here is to pass the log data into a shared cloud-based database and thereby easily combine discarded wood resources from multiple sawmills. Matching algorithms, like the ones created for this project, could then make use of thousands of logs to find the best solutions. Information like species, age, and location would then also be available, and the selection of logs could be limited or expanded to include local or regional logs depending on the type of construction. Likewise, a sourcing optimization could ensure that logs are selected from either a limited number of or only neighboring sawmills.

A reference platform could be the harvestmap.org (‘Harvest Map’ n.d.) project that is based on re-distributing surplus or redundant building materials. Here, architects, builders, and others can source cheap leftover materials from industry, construction sites, or redundant buildings and let those materials define or influence a new building. While a platform like this is not planned development work within this research project, the intention of the research is pointing in this direction. The intermingling of physical and digital resources has reached a level today where it often does not make any sense to separate the two. A quality of a material is no longer just defined by the material properties, but just as much through its ability to be handled, specified, and processed within a digital environment. On-demand and customized manufacturing are highly reliant on informed workflows where architectural specifications and material properties and availability is always connected. In such workflows, intelligently optimized, and sustainable architectural solutions, like the ones suggested in this paper, could exist.

CONCLUSION
In this paper, we propose a method that uses the natural shape of irregular wood as starting point for realization of a lamella roof construction. We have established a custom workflow that links precise geometric information about the stockpile with robotic processing of the material in a standard software environment. The method enables a close negotiation between material properties, design intent, fabrication process and the realized result.

To optimize efficiency, the workflow is developed to reduce
the amount of data that needs to be handled to a minimum. For instance, the heavy point cloud from the scanning is reduced to lightweight geometry thereby allowing a real-time representation of the final result.

An algorithmic design method has proven crucial for creating a direct connection between the available logs and the parts needed in the construction – and maintaining of this link throughout the workflow from scanning to fabrication and assembly. The handling of the latter needs to be addressed in future research, however, the relational logic between the parts necessary for developing assembly strategies is established.

Procedures for scanning and analyzing the stock material as well as sawing and milling technologies are already found in the wood industry. We find it feasible to establish design-to-production workflows using irregular wood that displays efficiency comparable to existing workflows.

The research shows how irregular shapes in nature can be linked and utilized directly in complex geometrical design. This is in contrast to an approach where a spatial intention is realized in engineered wood and machining without regard to the properties of the original material. The methods described in this paper can be seen as novel inspiration on how to optimize material use and induce rationality in irregular shaped architecture (see Figure 21). The added time, attention and knowledge required to utilize these diverging materials are not considered an obstacle, but instead regarded a direct way to obtain constructions with intended freeform appearances. We see an aesthetic, structural and sustainable potential in using irregular wood in buildings. The variation, tactile and geometrical qualities found in nature can become rewarding parts of the resulting architecture.

21 Crooked sawlogs machined into building components can be a rational solution for realizing curved structures; the curved leftover wood can then become a catalyst for new spatial designs.
REFERENCES


IMAGE CREDITS

Figure 9: Work and photos by 2nd year students at Aarhus School of Architecture. All other drawings and images by the authors

Niels Martin Larsen is an architect and Associate Professor at Aarhus School of Architecture in Denmark. Niels holds a PhD in the field of computational design, and he has undertaken private practice as well as projects for Danish architectural firms. His research evolves around algorithmic design methodology and focuses on developing integrated design-to-production workflows.

Anders Kruse Aagaard is an architect and researcher with a special interest in materials and digital processing of materials. Anders’ research has involved a broad array of material related to the building and construction but has in recent years focused on wood. Anders holds a PhD and is currently employed as Assistant Professor at Aarhus School of Architecture.