Timber tectonics in the digital age: interdisciplinary learning for data-driven wood architecture

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ABSTRACT: Timber architecture is being revitalized thanks to the development of advanced engineered wood products. Pioneering buildings are showing how digital design and fabrication tools are opening up new technical and aesthetic opportunities. Still, the industry faces challenges in the attempt to achieve full integration of the different phases of production, such as effective communication among stakeholders and seamless workflows. The *Timber Tectonics in the Digital Age* class, a collaboration between Oregon State University and the University of Oregon, exposes students to the challenges of integrating digital modeling, structural simulation and wood construction into a design and detailing project, thus reflecting what industry faces as it modernizes. Wood science, engineering and architecture students, embodying the three roles of manufacturer, engineer and architect, analyze classic structural systems and how they are being updated through new design and fabrication technology.

1 INTRODUCTION

1.1 *Forest products and wood construction in Oregon, USA: a new generation industry*

The forest sector is a historical industry in Oregon, which has provided jobs for local rural communities for decades. According to statistics reported by the Oregon Forest Resources Institute (https://oregonforests.org/content/economics), 61,000 direct jobs throughout the state are related to this sector, including forest management and forest products manufacturing and distribution, for a total of about 3% of total statewide employment. However, since the implementation of the Northwest Forest Plan in 1994, which shifted 11 million acres of federal forest land from timber production to old-growth forest protection, timber harvesting and traditionally related jobs have decreased significantly (Chen and Weber, 2013). To counteract this phenomenon, a number of recent, federal and state rural economic development initiatives have focused on relaunching this sector, promoting the use of mass timber as a sustainable building material for nonresidential and multistory structures, and actively supporting the development of advanced wood products markets and manufacturing.

The Oregon Building Codes Division has been instrumental in getting mass timber buildings permitted, and as a consequence, growing number of public and private mass timber projects are in development, under construction or have been completed in the state.

These initiatives are expected to renew and breathe new life to a conservative and traditional industry in most of the USA.

This momentum in the timber construction industry is fueled and supported by many nonprofit agencies and research institutes. Among them, the TallWood Design Institute is a unique collaboration, between Oregon State University (OSU) and the University of Oregon (UO), joining the College of Forestry's Wood Science and Engineering Department and School of Civil and Construction Engineering at OSU, and the Department of Architecture at UO. The institute provides

research and educational support to professional and industry, placing itself as a national hub for expertise in innovative wood building design.

Educational activities under the aegis of the TDI include the *Timber tectonics in the digital age* collaborative course between OSU & UO, as well as early introduction of cross-disciplinary AEC contents to Wood Science undergraduate students (Riggio et al. 2016), and interdisciplinary research-design studios involving Architecture and Engineering students (Donofrio et al. 2016, Sheine & Gershfeld, 2018). The *Timber tectonics in the digital age* course was launched in 2016 to give the wood science, engineering and architecture student an opportunity to take the role of manufacturer, engineer and architect in a design and detailing project. One teacher leads on timber architectural structures and the other on parametric deisgn and analysis.

The aim of this course is to develop hard and soft skills needed by the today's wood products manufacturing and construction industry, thus reflecting what industry faces as it modernizes, to advance and expand beyond the market sectors traditionally occupied by wood: commodity products and low-rise, residential construction.

1.2 *Digital technologies and Engineered Wood Products: a perfect match*

New advanced engineered wood products, and digital design and fabrication techniques are transforming wood architecture. Buri and Weinand (2011) defined three technological ages, which have influenced the tectonics of timber structures: a pre-industrial age, in which the carpenter is the designer and constructor of unique products within a consolidated tradition; the industrial age, leading to product standardization and disciplinary specializations; and, finally, the current "digital age". Parametric design has eliminated the old divide between different design stages and tasks, blending architectonic and engineering efforts. In timber architecture, this means being able to incorporate at the early stage of the design, considerations of materiality, machinability, constructability, which otherwise, if incorporated later, can require deep alterations of the original concept.

Research-lead pilot projects show how combining material consideration with parametric design and digital fabrication opens up new technical and aesthetic opportunities. For example, Robeller, Nabaer and Weinand's curved CLT demonstration pavilion (2014) shows how a laminated timber structure can be pressed into a curved shell, and then tailored for custom joints using robotic cutting. The stability of the delicate structure depends on the coherence of the timber members, the form's curvature, and the craftsmanship of the cutting and assembly. To produce this kind of innovative structure, requires developing and integrating expertise about materials, design, engineering and construction.

2 TIMBER TECTONICS IN THE DIGITAL AGE AT OSU-UO

2.1 *Learning objectives*

Education provides a microcosm to see how the challenges of new technology will be encountered. The class replicates a real-life scenario, where inter-disciplinary collaboration is activated at an early stage of the creative process. The *Timber Tectonics in the Digital Age* class teaches about timber structures and material properties, with skill building in digital modeling and structural simulation. Students are challenged to collaboratively apply the knowledge and skills in the design, detailing and construction sequencing of a group project.

Learning objectives of this course address the development of both hard and soft skills considered critical by the today's Architecture, Engineering and Construction (AEC) sector (Gann and Salter, 1999, Fouger, 2008). Hard skills include: a) understanding the interactions of material science, technology, architecture and engineering, and demonstrating their synergies through design applications in wood structural systems; b) understanding the historical evolution of the AEC industry, through examples of design, manufacturing and construction strategies used in timber buildings; c) developing a knowledge of digital techniques for the design, manufacturing and construction of advanced wood structural systems; d) developing analysis and synthesis skills through the applications of design principles in small scale projects.

Besides the disciplinary (or better inter-disciplinary) content knowledge, fundamental learning objectives include the development of soft skills, including teamwork and cross-disciplinary communication. These skills are critical as the industry still faces challenges in achieving full integration of the different phases of production, including effective communication among stakeholders and seamless workflows.

2.2 *Course content and format*

The course develops in one term, for a total of fifty hours distributed in ten weeks. Classes are delivered as interactive lecture/hands-on sessions. Lectures are delivered synchronously in the two campuses, separated by one hour of driving time, in Corvallis (OSU) and Eugene (UO), via teleconference. The class meets face-to-face four times during the term; for the initial presentation and team-building, two intermediate project review meetings, and a final presentation.

In the course, fundamentals of wood tectonics and architecture design are explored. These include mechanical behavior of wood and its influence on the structural system; static principles of wooden constructions and their influence on the architectural form; wood connections behavior and detailing; solutions for durability; relationship between general properties of wood as well as product-related properties and applications; compatibility with other materials; design alternatives employing innovative uses of advanced wood products.

Five thematic modules distributed in the first five weeks expose students to applications of engineered wood products and parametric design tools and show how timber structural systems are being developed through new design and fabrication technology. These systems include: columns and beam, frames and trusses, arches and domes, shells, grids and gridshells, plates and folded plates.

Students learn simulation software by modeling and analyzing versions of the structural systems, starting simply and then developing more complex variations. Software skill building complements learning about the special requirements of wood, by examining material applications, design solutions and assembly processes of case studies. To enhance learning, students keep a weekly journal. They create annotated lecture notes and reflect on their design visualization and analysis efforts. The students manage a class blog, where they post selected pages of their portfolios and comments on compelling class topics (https://timbertectonics.com/about/).

In the last half of the course, students apply their skills and knowledge towards a team project, devoted to the design, analysis of a wood pavilion and prototyping of connection and construction details.

The class project is a small-scale building: an outdoor and an indoor pavilion, for the first (2016) and second (2017) editions of the class, respectively. Students are encouraged to use the structural systems studied in class to design the pavilion, showcasing the use of different engineered wood products, according to the specific structural needs. Precise design constraints were determined for each project, such as durability and maintainability for the outdoor pavilion and easy transport, constructability and de-constructability, for the indoor construction. The primary software tools are Grasshopper (Ericson, 2017) and Karamba (Preisinger & Heimrath, 2014) plugins for McNeel's Rhinoceros for integrated parametric design and structural analysis. These are coupled with material prototyping, to verify mechanical/structural behavior and constructability of connections and assemblies. Prototyping includes use of traditional wood shop equipment and digital fabrication tools such as 3D printers, laser cutters and CNC machines. Material testing is sometimes required, for some projects, to verify design and analysis assumptions (e.g., lath bendability, etc.).

The class is enriched with guest lectures from the AEC industry and wood industry, whose real-time input explains how to address emerging challenges of the rapidly changing industry.

During the review meetings and the final presentation, students present their projects to a group of reviewers composed of members from the professional, industrial and academic world.

2.3 *Student demographics and team composition*

Students in the course come from different programs at Oregon State University and the University of Oregon. The course is available to both advanced undergraduate students and graduate students. OSU students from the Wood Science and Engineering department are either enrolled

in the Renewable Materials (RM) Bachelor of Science degree program, or the Wood Science graduate School. OSU undergrad and graduate Engineering students come from either the programs of Civil or Construction Engineering. The University of Oregon students have generally come from the accredited professional Bachelor or Master of Architecture programs in the School of Architecture and Environment, part of the College of Design.

This varied student demographics has been taken as an opportunity to test teaching styles appropriate for a heterogeneous learners' milieu, as well as to activate communication and workflow strategies within the teams, which should mimic emerging inter-disciplinary tasks.

Given the different knowledge, expertise and interests of the students, one of the main educational challenges is to deliver content that can be assimilated by the novices and still stimulate the experienced ones. This is true for every class aspect: i.e., parametric design, engineering and material science.

Each student, as an individual bringing expertise in a specific field in the AEC sector, is asked to contribute actively to the team, through her/his experience, and encouraged to explore her/his interests within the course.

While much of the course takes place online, team formation is seeded by meeting face to face during the first week of class. Students engage in team-building activities during this meeting (Figure 1). Pairs or triplets of students interview each other and create online profiles. The intention is that the profiles act as advertisements in a kind of marketplace that assists students in choosing partners with complementary expertise.



Figure 1. First week team building activities.

2.4 *Reflections from journaling activities*

Work-in-progress journals or e-portfolios require the students to take responsibility for directing their learning, and provide to the instructors feedback about the students' ability to grasp presented materials. Students are asked to reflect on how lectures, readings and personal experiments contribute to their weekly learning objectives and overall course goals. Students snap images of items of interest and of their modeling exercises, and write one to three paragraphs about the information, compiling a graphic scrapbook, that is an excellent tool for review after the course. The journals present student achievement in context, allowing a more individualized instructor response.

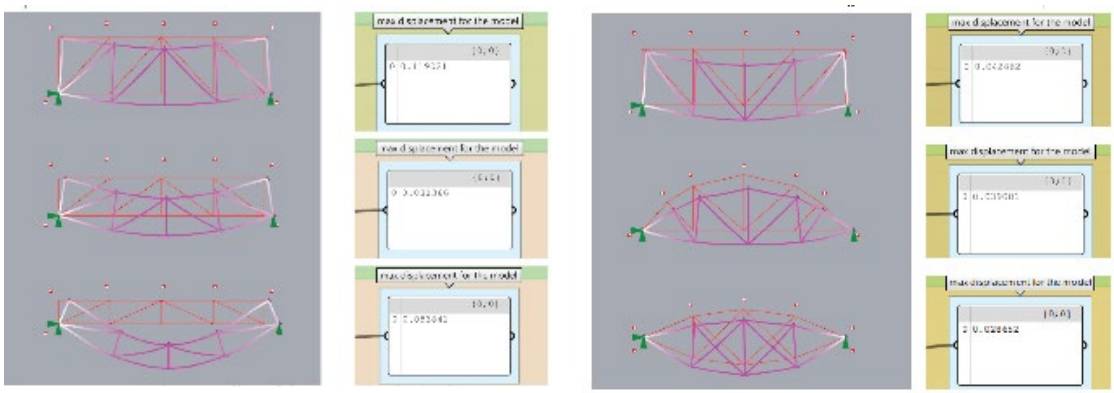


Figure 2. Work-in-progress portfolio pages show how truss shape affects deflection.

2.5 *Project Outcomes*

In the two editions of this course, design of the team projects has been dictated by two main driving forces: the geometric shape (in many cases, form-resistant, and parametrically designed) and the structural and materials constraints (e.g., load paths, timber connections, use of linear or panel-based engineered wood products, etc.). When these driving forces were instantiated in two consecutive stages, one of the recurrent outcomes was that the project development was characterized by a drastic shift from one system to another, sometimes even in multiple iterations. In this case, vestiges of the elements characterizing the initial driving force (e.g., the shape) were partially recognizable in the final iteration. One of the examples of this category of projects is a spatial, reticular system developed from a structure initially conceived as gridshell and then evolved in a free-form-based, folded plate system (Figure 3). The radical change of direction in this project was motivated by the need of designing a system composed of transportable modules, which could be connected easily and effectively transfer loads from one element to the other. Precedents using integral joints for folded plates (Robeller & Weinand, 2015) were initially considered, but this option was then rejected, for the complexity of implementing it in a deployable system. This brought to the radical choice of "stripping the flesh" from the plates, leaving the "bones" of the folding lines. The connections transformed consequently from linear fingerjoints along the creases to point nodes at the intersection of the linear elements.

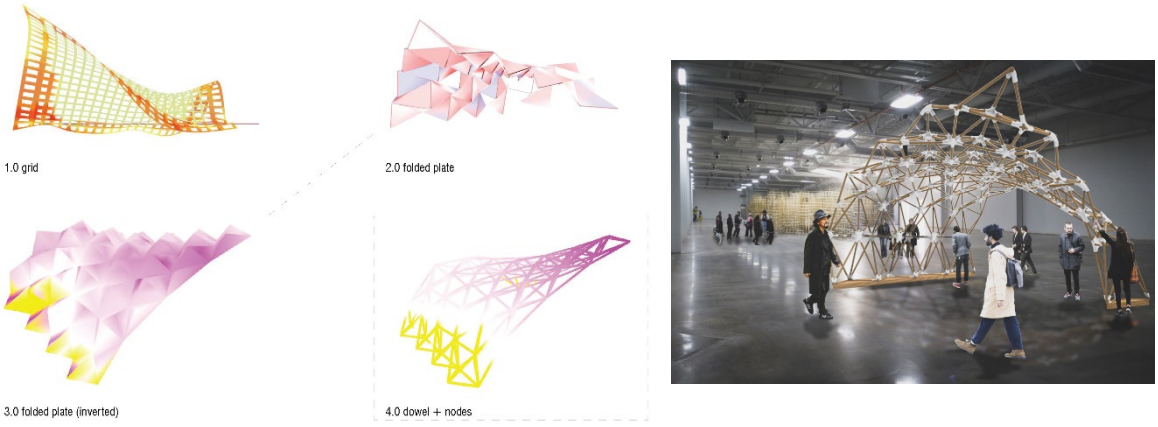


Figure 3. A pavilion project which experienced radical design shifts.

A more continuous evolution of the project concept, from the early stage of the design to the final stages of the construction detailing and prototyping, is observed in projects where the two tectonic-driving forces (form and structure) coexist from the beginning. In these cases, a team worked on an incremental development of a project idea, based on further refinements of the initial concept. As an example, Figure 4 shows the early concept and final design for a gridshell. Because the team met most project requirements early in the term, they had less opportunity to

learn by comparing alternative options. This tunnel-vision can be overcome by either requiring students to carefully critique peer solutions or requiring them to illustrate alternative options at increasingly refined scales throughout the design process.

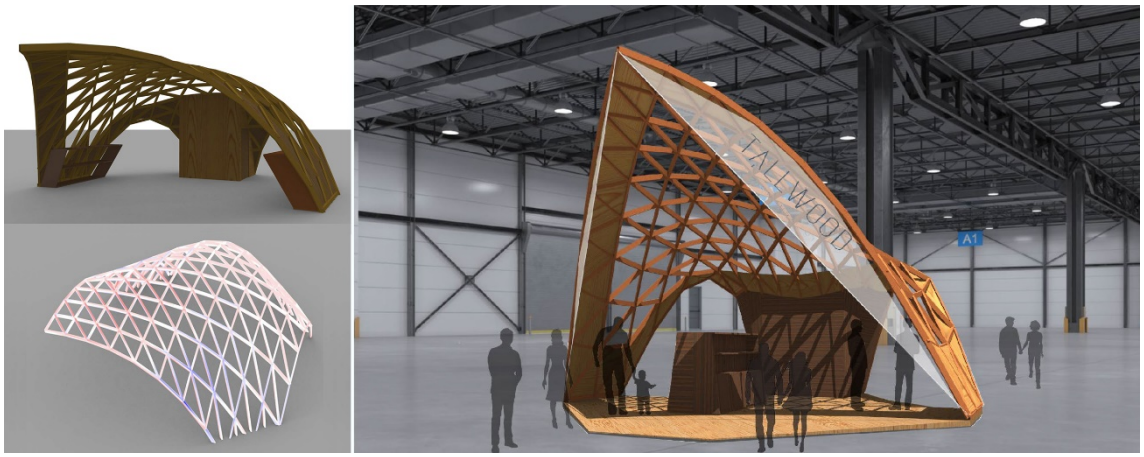


Figure 4. Example of an incrementally developed tectonic project. Left: First (week 5) and Right: final iteration (Week 10) of a gridshell.

Incremental and radical development of the project can be seen as externalization of two diametrically opposed learning processes: an incremental advancement of prior knowledge and steep learning curves, corresponding to acquisition of new knowledge and development of new skills.

Additionally, these two approaches are somehow reflected in the team dynamics, i.e., well established roles and continuous interaction in the team *vs.* more blurred expertise distributed among the team members. These different team dynamics are further discussed in the following section.

2.6 *Team dynamics and interdisciplinary skills development*

In putting together students from different disciplines, it was hard to overcome the natural authority that comes from design experience and software expertise. Originally, it appeared that the architecture students dominated the group project direction because of their role as design leaders. While all students can discuss ideas, those who can sketch provide a focus for articulating the design ideas and naturally gain a leadership role. In the preliminary steps, students with technical knowledge of timber, engineering or construction sometimes were less involved as their expertise was seen as coming later in the process. The collaboration is dependent on strong listening and responsive feedback.

Furthermore, because the projects were developed using a particular software platform, expertise with this software defined the leader of the design. As there was not an easy way for multiple hands to be on the mouse, the designer who could visualize and analyze the projects became the de-facto main author of the project. This was especially true for the projects whose geometry as well as the analysis was done in Grasshopper parametric design

The dominant authorship of the computer expert was mediated by team members who initiated physical fabrication of joints or prototypes. The physical models provided a more intuitive understanding of construction challenges and structural stability issues in comparison with the digital models. While the Karamba software is good for creating parametric form and overall structural analysis, it does not articulate the anisotropic structural properties of wood.

Students appreciate even being able to see and feel the weight of many kinds of timber products. Developing a strong understanding of material properties and joints, requires regular woodshop sessions. Those teams who engage in physical prototyping early in the process have a better intuitive understanding of structural challenges. Architecture student who was agile with parametric design and visualization become enamored with virtual forms that have little structural stability. They might be able to run a structural analysis of a geometric form, but are challenged to set up the simulation accurately and interpret the results.

When students build joints and assemblies, even at a small scale, they are immediately confronted with practical fabrication and construction issues. While digital elements are easily spawned, aggregated and manipulated, multiplying physical elements quickly generates complex assembly challenges. Students physically modeling an overall form can immediately understand how joint rigidity influences stability. Students working at a larger scale can understand the challenges of construction sequencing and the relationship timber properties, product-specific features and connection techniques.

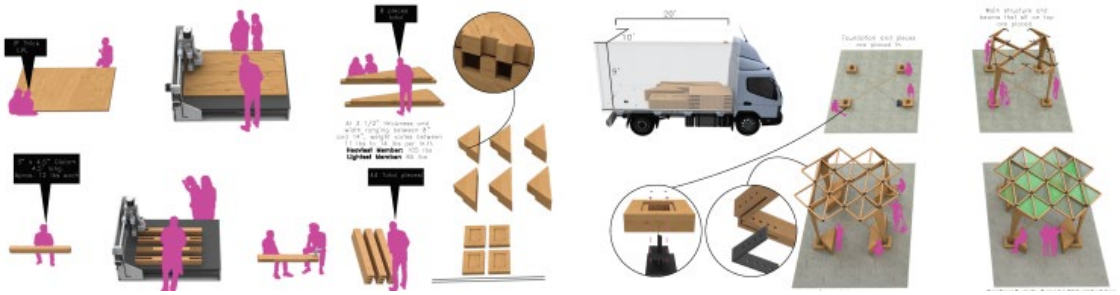


Figure 5. Renderings showing off-site pre-fabrication (left) and on-site pavilion assembly (right)

3 CONCLUSIONS AND FUTURE ACTIVITIES

Despite the clear need of developing interdisciplinary courses to increase the exposure of students to wood construction and emerging parametric tools, some challenges exist, which encompass cultural, pedagogical, programmatic and logistic constraints. These include administrative obstacles to coordinating different departments or schools, and logistic challenges to access to resources and spaces that are not co-located, etc. Varied disciplinary conventions limit class hours, make it challenging to cover design through construction. Digital design and construction requires different spaces with some flexibility. Teaching structural concepts, digital design software and hands-on construction is best done in different environments: classroom, computer lab and wood workshop respectively. In the case of multi-disciplinary groups of students, coming from different institutional partners, access to common working spaces can be even more challenging..
While time constraints, technical support, safety and liability issues make it complicated to arrange hands-on construction experience, it is clearly invaluable for students to make progress in timber design and fabrication

Communication challenges, due to differences in backgrounds and jargon, are exacerbated by remote communication. Consistent high-quality audio is crucial for remote learning. Adding face to face sessions and reducing connection time can overcome the awkwardness of video-conferencing. We included a software workshop prior to the term, and added traveling teacher visits to the remote campuses. For the future, local or traveling tutors could support software and woodworking efforts and a “flipped classroom” model of pre-recording lecture and software demonstration videos would allow for more in-class interaction.

Mixed teams will yield different kinds of learning according to individual roles. Even students who take a less active role can write thoughtful reflections and exhibit growth. A balance must be made between individual and group requirements. Assignments for individuals can ensure more rigorous training, but subtract time from learning about collaboration. Within the group project, requiring team members to articulate their roles and tasks, continuously updating a plan of deliverables could help instructors monitor contributions. Teachers need to help partners identify each others’ talents so that each member can thrive.

Overall, students greatly value the AEC collaboration opportunity and enjoy seeing cutting-edge buildings and research. Architecture and engineering students particularly appreciate learning about timber’s unique characteristics, and the Renewable Materials majors are glad to see architectural applications of wood. Even students who gain only limited proficiency with design and software, can see its potential through the work of peers and professionals. The journals and blog provide a concrete record of their growth and competency.

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