Abstract. A dual university collaboration challenges students in architecture, wood science and engineering to partner on a timber design and detailing project. Five years of student projects reveal how the mix of backgrounds, design media abilities and design development process impact the learning experience. Team design submissions, individual reflections and observed collaboration activities were analysed along with patterns of design ideation, transformation, and conflict resolution. Learning experiences vary according to the mix of student backgrounds and roles within the team. Teams mixing students of different levels and backgrounds on average performed better than more homogenous teams. While beginners do not have the skills to play a central role in the team, they have the most to learn from more advanced students. Keeping all team members engaged may require giving up some efficiency of a streamlined digital workflow.

Keywords. Digital Collaboration; Architectural Education; Integrated Design; SDG 12; SDG17.

1. Introduction - training for 21st century collaborations

Timber design and construction has been evolving rapidly with technology affecting forest management, engineered materials, prefabrication, and construction automation. New digital workflows are being pioneered that extend from forest to factory, with 4D planning for construction and building management. This process requires agile technical skills to nimbly bridge between disciplinary and global boundaries, as in the United Nations Sustainable Development Goal (SDG) 17 Partnerships to achieve the goal (2021).

Digital collaboration skills are particularly crucial as the timber industry adopts pre-fabrication, integrated design and optimized construction processes that rely on robust Building Information Models (BIM). The European leanWOOD project identified factors including scarce IT-literacy and limited interoperability as hindering full technological adoption (le Roux et. al, 2016). Staub-French et. al. (2018) explains that for the growing mass timber industry, BIM needs to be consolidated with Design for Manufacturing and Assembly (DfMA) with data sharing across the supply chain. Digital component descriptions are crucial for efficient production and assembly of
1.1. COURSE DESCRIPTION

To prepare a new generation for this quickly evolving environment, the Timber Tectonics in the Digital Age course immerses students into interdisciplinary partnerships to learn parametric design, structural analysis, and construction prototyping. The course is predicated on the belief that parametric design is best learned with simulation for design assessment and learning occurs most effectively through applied team design scenarios. The Timber Tectonics in the Digital Age course is jointly and concurrently taught to Architecture students at University of Oregon and Wood Science and Engineering students at Oregon State University. This paper describes how the course has evolved and lessons learned from five iterations of teaching digital workflows for AEC collaborations. The students work in cross-disciplinary small groups to design, detail and prototype a small structure.

The course introduces archetypal structural systems and how digital methods are facilitating innovation in structural efficiency. Historic and contemporary examples illustrate how timber forms and connections maximize the capabilities of the material. Students use Rhino Grasshopper and Karamba to generate geometric variations of structural systems and the effects of form transformation on structural behaviour. They are asked to apply the structural principles, material understanding and software skills in the context of a collaborative design challenge. In small groups, students brainstorm and find a design direction, and after then, identifying appropriate timber materials, they develop, detail and prototype assemblies of increasing scale, as allowed by wood shop access.

Our pedagogical approach is based on Bloom's Taxonomy (1956) that shows student learning retention is improved via active application of concepts in project-based learning, the heart of most design studios. The learning pyramid's hierarchy endorses that interacting with concepts, as occurs in team peer-teaching and negotiation, helps student retain skills and knowledge. We have been operating on these additional assumptions:

- Experiential hands-on applied learning can help students understand structural principles, material properties, and digital/physical tool capabilities and limitations.
- Students educated together about common content can apply this knowledge more smoothly in interdisciplinary teams due to shared vocabulary and greater interoperability.
- Practice with collaboration tools will prepare students for future remote digital partnerships.

The design project's scale is small and program simple to keep the focus on tectonic design and construction. In the first three years, students designed a small pavilion for a campus location. For the fourth iteration, the Architecture course was changed from a seminar to a design studio to provide more time for project development and the design program was enlarged to a full community design. Students were asked to design housing for refugees from wildfires, houselessness, or political strife, with small self-build cabins and a long-span community centre. This allowed students to learn about trauma-informed design, site design and envelope detailing appropriate to SDG guidelines.
Since the expanded scope also divided student energy across many issues, for the fifth iteration in 2021, the focus returned to a relatively small pavilion - a nomadic modular performance stage. The requirement for portability, ease of construction and deconstruction focused student energy into pre-fabrication and on-site assembly. The re-usability of a seasonal or event-based structure reinforces the SDG 12 Responsible Consumption and Production.

All versions of the course began with an introduction to the context and accelerated getting-to-know-you activities for quick team formation. Students interview each other with prompting questions and write simple profiles for a marketplace of partners. Students self-organize teams around the guideline to find complementary abilities.

Students are introduced to structural systems that progress in complexity to correspond with the gradual development of parametric design skills as in Figure 1. This begins with structural systems made of linear elements: first section-active systems (columns, beams, and frames) and then vector-active systems (trusses and dendriform structures). Hands-on workshops teach Rhino navigation, vector drawing, Grasshopper parametric basics along with Karamba structural analysis. Beginners stay in 2D while the more advanced proceed quickly to 3D forms. Students can import geometry from other programs for analysis, albeit without fluid parametric adjustability.

After linear elements, planar elements are introduced, beginning with grids, plates, and folded plates. Once the students understand the operations of defining elements, supports, loads, cross-sections, joints, and material characteristics, they learn about Form-active systems (cables, arches, vaults, and domes) or Surface-active systems (shells and gridshells). At this point, students also learn how to use the parametric design tool for form-finding with buoyant forces. The students choose from these systems to develop their design project. External experts contribute guest lectures and review the projects three times during the term.
Course delivery began with two parallel Canvas sites and WebEx video conferencing in 2017. For Fall 2020, the fourth version of the course, lectures and tutorials were recorded to enable a flipped classroom format (Bishop et. al. 2013) that maximizes large and small group interaction over live Zoom connection. Microsoft Teams and Miro whiteboard were added to provide more immediate interaction and tracking of communication for both small groups and the entire blended class. Students from the two universities meet in person at the start of the course, for a first introduction and team building activity, and at the end for the final review.

Project quality is assessed on the following criteria:

- **Architectural design**: Integrates the construction into a graceful, coherent form that meets all functional & site requirements. Explains the user experience.

- **Structural thinking**: Optimal use of material and structural elements/systems, proven by structural models.

- **Digital methods**: Shows the relationship between geometry and structural forces through design variants

- **Material understanding**: Wood products are well-chosen according to properties such as mechanical properties, durability, and workability

- **Fabrication/Construction**: Explains how components would be created, sourced and assembled. Describes the construction and deconstruction process. (Figure 2)

Figure 2. Storyboard shows processes of pre-fabrication and on-site construction

2. Methodology and prior analysis on interoperability and collaboration.

To identify ways to improve the course, we began this study by focusing on how interoperability, the ability to share data, correlates with a team's collaboration success attributes (Riggio and Cheng, 2021). Our qualitative methodology characterized each project according to collaboration indicators and interoperability achieved while also considering the major project drivers and types of design media used. For each project, we examined three successive rounds of student self-assessment reports and design presentations in order to assess and tabulate the qualitative attributes. We checked for
collaboration indicators (explained by Tran 2013, such as task coordination, effective assistance, constructive feedback and exploring different points of view) and student engagement via the written and graphic documents. Final project grades reveal the team's success in addressing course criteria. Main findings from this analysis:

Teams with strong interoperability were able to coordinate concurrent work and showed high coordination with equal sharing of work. Conversely, cases of poor interoperability were more frequently characterized by a sequential division of tasks and poorer coordination among team members. Individuals needed initial time for free exploration before finding a common design direction that allowed them to better coordinate tasks. While teams could try to assign roles at the beginning of a project, it took some time for them to develop a deeper understanding of each other's abilities and work styles (through both synchronous meetings and seeing team members' work). Once the design direction was established, teams found ways to work in a more coordinated, concurrent fashion, with or without data interoperability. Teams that were unable to seamlessly share 3D project data typically would export or reconstruct information with a loss of efficiency and/or consistency.

The initial design driver influenced whether the team's project development path was direct or convoluted. Those teams that started with a structural or construction concept could more efficiently and deliberately develop their project through material choices, component and connection choices and construction assembly sequencing. In contrast, those who generated their design project using a visual inspiration or design metaphor often would need several design revisions to find a constructable form.

3. Factors shaping the student learning experience

This paper builds on the methodological approach used in our prior study to focus on the range of student learning experiences. We examine the mix of student backgrounds and the number of designs schemes considered and expand the analysis from the first three iterations of the course to include the fourth and fifth versions which have the same learning objectives, albeit with amended course delivery mechanisms. We are interested in how a student learning experience is affected by 1) an individual's position in a team's mix of disciplines and seniority, 2) an individual's ability to share 3D project information and 3) incremental or radical design shifts.

3.1. TEAM MIX, COLLABORATION & INDIVIDUAL LEARNING

Teams have had three to five members, with students ranging from third year undergraduates to third year graduate students, from majors including Architecture, Civil Engineering, Wood Science and Engineering, Construction Management and Architectural Engineering. We rated the groups from 0 for completely homogenous to 3 for extremely varied. Figure 3 shows that on average, higher project quality correlates with students from more diverse academic levels and disciplines, but individual projects reveal that the student mix is neither necessary nor sufficient to guarantee success. Motivated students produced strong work in both homogenous and diverse groups.
In groups with a wide range of academic or professional experience, a natural leader often emerged, which helped in delegating tasks and negotiating design decisions. Consistent with Tucker and Reynolds 2014, groups without a senior member could become frustrated with the lack of hierarchy. A student said having equal status made it hard, that it was easier to make decisions when there is a boss. For this reason, in 2021, five Architecture post-professional graduate students who originally wanted to work together were grouped with less experienced students to spread their experience and reduce competition. Each one became a successful team leader.

Groups with students from different disciplines could more easily assign specialized complementary roles. Team members were more likely to stay engaged in non-overlapping tasks that required responsibility, provided autonomy, and gave a chance to shine. The digital whiteboard helped track task completion.

Within these groups, the students had varied learning outcomes. Given the robust course agenda, students specialized according to interests and prior knowledge. So often they learned one aspect deeply and gained awareness of aspects completed by others. While some of the strong projects came out of well-balanced collaborations, others came to a strong result due to one or two dominant members. In the first few years, those with the strongest Grasshopper-Karamba skills became the team leaders and others played more supporting roles. When team members were asked to rate the contributions of their small group members, there was often agreement about who contributed the most and who contributed the least, though they portrayed varying magnitudes of unequal contributions. While some team members resented having to shoulder more work than others, the asymmetry did not necessarily yield a weaker project outcome or poor learning for the less active member, consistent with Tucker and Rollo’s observation of team design studios (2006).

In many cases, the students with less experience, who played supporting rather than leading roles, enjoyed working with agile, more experienced students. Even if it wasn’t their own hands working on the computer or driving the CNC machine, they were able to observe the incremental development process up close and appreciated the substantial contributions of others. In contrast, two more experienced students reported...
less satisfying learning experiences. When one of the more agile designers surprised team partners by presenting an individually developed design idea as the team design, the person reflected that "it felt like the fault fell on me for producing work 'too fast', but the other student was moving at a pace too slow for a studio course." While most of the students expressed gratitude for the opportunity to work in interdisciplinary groups, one grad student expressed that the teamwork was redundant with a prior professional office experience, echoing Tucker and Abassi's finding (2014) that mature students were less satisfied with the teamwork process than younger peers.

3.2. ABILITY TO SHARE 3D INFORMATION AND LEARNING

In a sense, the non-architecture students operated in foreign territory because the course is dominated by architectural software and by architectural education conventions such as graphic presentations, qualitative feedback, and integrated design. Some of the most effective groups found ways to shift the project to more familiar ground for the Wood Science and Engineering students, who commonly are responsible for identifying appropriate connection techniques or hardware. They have captured the imagination of classmates when they have additionally performed structural testing on wood samples, such as measuring the bending ability of wood laths or taken the lead on prototyping.

Similarly, structural engineering students have flourished when they could perform either SAP2000 or hand calculations that inform the process. While taking the model out of Grasshopper breaks the parametric interoperability, the activity boosts the collaboration and has not impeded much of the workflow (Figure 4). Students see the value of the parametric adjustability in conceptual design; exporting to other platforms can efficiently support a more detailed analysis once the design is set.

Figure 4. Exporting the model for analysis breaks the quick feedback cycle but could enable engineers to flourish. Filled shapes represent the digital workflow, outlined can be independent.

The ability to describe and share information is key to being an active design participant. In the first ideation phase, students who can show their ideas through sketching, cardboard or digital models can engage peers and invite further
Those without visualization abilities must use words and visual examples. As the team considers parametric variations and structural stability, students who are most adept with the software often assume a leadership role. To have a voice, students must be able to interact with 3D information. Those who lack data sharing skills can only act as consultants or helpers, as they must work with a static snapshot rather than driving the active model. Well-organized teams can separate tasks, such as creating an abstract line model for structural analysis vs. a robust model for physical prototyping and visualisation. Less experienced students have provided valuable support through researching structural, material and construction options. With peer guidance, they can develop subassemblies and contribute graphics.

3.3. INCREMENTAL OR RADICAL DESIGN SHIFTS AND LEARNING

Groups that take a more circuitous route to the final design project have to consider a wider range of structural and construction issues, while those who initially have a viable scheme instead focus on subtle refinements. Students with experienced team members often started with a strong idea based on a structural system that they could efficiently develop and detail. In their incremental process, they do not experience as full a range of parametric exploration as those who have more false starts. Those students taking a more indirect path have to consider, discuss, and evaluate alternative design options as in Figure 5. This aligns with Emam et. al. (2019, p. 164) view that collaborative design is effective for learning because students need to find a direction through team discussion and active negotiation.

Figure 5. This team generated a sequence of options for the modular stage and had to deliberate about each one’s structural stability and aesthetic expressiveness. Final is on the right.

4. Challenges and Attempted Remedies

Unequal playing field: A major challenge is how to have parity between students of different backgrounds as less experienced students can feel overwhelmed or disenfranchised. For example, our architectural engineering, civil engineering, and construction management students enter the course without experience in Rhino Grasshopper, while architecture students have earlier initial exposure. Architecture students generally take the lead as the engineers want a definite form before starting structural analysis, even though we encourage bottom-up thinking about materials, structural systems, and modular constructions. One student offered a possible remedy to how the course caters to architecture students, "Maybe engineering students should be introduced later in the term…. I feel like that is more realistic in the process of a real project…. Maybe during the time period [architecture] students are designing, other
students [could be] properly taught how to use Rhino and Grasshopper."

**Differential class meeting times means imbalanced participation:** As in any collaboration, differences in disciplinary conventions must be bridged. An unforeseen consequence of moving to the design studio class for the Architecture students has been to greatly imbalance the amount of participation for the two universities: While the Architecture students spend 12-hours per week in class for six-credits, the Wood Science and Engineering students only spend 5-hours per week for four credits. The synchronous videoconference was typically split between large group activities and small group collaboration time with roving instructor conferences. While this schedule provided a predictable rhythm to the class, it precluded extended discussions or workshop sessions. As a remedy in future years, it may be possible to offer a studio course for more credits to the Architectural Engineering students to give them more parity and provide more intensive software training.

**Challenges with remote communication tools:** Students eagerly engaged multiple digital communication platforms during Fall 2020, the first year of the pandemic. An MS Teams forum called "Ask an Expert" fostered lively discussion between students, reflecting their interests and importantly provided a chance for Wood Science and Engineering students to shine. On returning to campus in Fall 2021, complaints about the proliferation of platforms arose as students expressed confusion over where to look for course information or feedback. It arose because students seeing each other face-to-face did not use MS Teams' mobile chat function and they preferred to set up private team chats without tutors. For the next round, expanded communication capabilities in Miro whiteboard could allow elimination of MS Teams.

The live Zoom video conference in class proved to be effective for instructor-to-class interactions, and it created audio problems when multiple groups in one room connected with different remote teammates. We improved these small group meetings, by splitting teams into multiple rooms, with some individuals joining remotely.

To foster better partnerships, we have increased teaching about the collaboration process with help from business school specialists. Students generally begin eager to meet from other majors. Then teams needed to work through different expectations, conceptual frameworks, work styles and vocabulary. To support agile team interaction, we added a workshop on project management and another on negotiation styles and strategies. The utility of the workshops depends on their timing within the team development process. For example, the teams were receptive to developing plans and roles according to the project management workshop guidelines. By the time the second negotiation workshop was held, students were less engaged. A student explained that they had already figured out approaches to conflict resolution. Students receive teamwork training information differently, according to their prior experiences.

5. **Lessons learned**

Five iterations of this course teaching integrated timber design have indicated that it has fostered awareness and appreciation of disciplinary perspectives and collaboration, and challenges to interdisciplinary learning still exist. Notably, the pervasive use of digital tools as part of the learning objectives and for the content delivery and collaboration has introduced some difficulties, such as unequal skill preparation for the
digital design process, redundancy of communication platforms and “digital burnout”
i.e. Zoom fatigue. Furthermore, pedagogical, programmatic, and logistic constraints
pose challenges in the development of interdisciplinary, inter-institutional courses (e.g.,
access to remote resources and spaces, class schedules, administrative obstacles).

Nonetheless, this course demonstrates the impact of experiential learning in the
development of soft skills highly desired by employers. Our study shows that vertically
integrated teams provide leadership opportunities for the more experienced and give
beginners a crash course in design processes. Even those who lacked software agility
or had a circuitous project development experienced a valuable immersion into digital
collaboration and peer-to-peer learning. The majority were able to find a useful role,
create productive working relationships and ended the term proud of the team output.
The microcosms of the student interdisciplinary groups show that teamwork must be
carefully planned to fully engage all capabilities into interdisciplinary collaborations.

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