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Case Report

Computation and Learning Partnerships: Lessons from Wood Architecture, Engineering, and Construction Integration

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Abstract: Examining an interdisciplinary university course for architecture, wood science, and engineering students, this paper studies how the students' ability to master digital workflows influenced their success in learning collaborative design skills. It highlights potential challenges and opportunities posed by the introduction of new digital tools to support emerging integrated building design in both education and professional practice. The particular course focuses on the wood industry, which is rapidly changing from a very traditional to a highly innovative sector and increasingly embracing the latest technological developments in computational design, simulation, and digital fabrication. This study explores the influence of parametric design on collaboration dynamics and workflow within an interdisciplinary group of students embodying the roles of manufacturer, engineer, and architect. Student-generated data of the first three years of the class is analyzed thematically to find correlations with productive collaborations. Focusing on a stage of an evolving teaching and learning process, this analysis allows identifications of common themes and patterns, suggesting implications for practice and future research. The course highlights the need to integrate data interoperability, collaboration skill-building, and material awareness in contemporary digitally enabled architecture, engineering, and construction education. The lessons learned in this course can be of value to academic programs and professional firms involved in incorporating digital design and interdisciplinary collaboration.

Keywords: interdisciplinary collaboration; integrated design; parametric design; wood construction; interdisciplinary education

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1. Introduction

Education in the field of built environment and civil engineering disciplines is challenged by the transformative shifts in the Architecture, Engineering and Construction (AEC) industry. A demand for tight-knit real-time collaboration is being fueled by the ubiquity of digitalization in all project delivery phases, from early design to fabrication and construction. These changes are contributing to replacing traditional, sequential collaboration models characterized by separate, dependent workflows, with concurrent models. In digitally enabled, concurrent models, the organization and hierarchy of design is characterized by "collective workflows", and "geometric, spatial and technical information is filtered through simulation, analysis and optimization processes" ([1], p. 8).

The wood construction industry is paradigmatic of these changes. As a matter of fact, timber as a building material is living a "new life", thanks also to the development of advanced engineered wood products, which are becoming widely popular largely due to their enhanced technical performance [2]. Computational processes and cutting-edge technologies have been finding fertile application in wood construction. Wood machinability makes it an ideal material for numerically controlled and robotic machining, thus transforming the traditional wood manufacturing industry into a high-tech sector, shifting production from commodities to mass-customized, high-end products (e.g., [3]).

Protocols such as Leadership in Energy and Environmental Design (LEED) certification [4] require an early integration of multiple perspectives. The demand for higher performing buildings as well as more efficient and more economical processes has been leading to a transformation of the bidding model in the construction sector: from the traditional sequential design–bid–build (DBB) contract to the increasing adoption of design–build (DB) models and integrated project delivery practices [5] that demand early and frequent teamwork. These transformations require a new generation of professionals consisting of individuals with a broad range of technical skills that can effectively communicate across disciplines (e.g., [6]), who are able to collaborate in a global and virtual workplace [7], and can stay ahead of the fast pace of technology advancements dominated by the increasing presence of digital data.

As collaborative skills are mandated in AEC disciplines based on the respective accrediting bodies, such as the Accreditation Board for Engineering and Technology (ABET) [8], the National Architectural Accrediting Board (NAAB) [9], and the American Council for Construction Education Accreditation (ACCE) [10], AEC educational programs have been developed, and new ones are continuously under development, to promote collaborative learning while setting the pace (or, sometimes, keeping the pace) with the technological innovations of the AEC sector.

These collaborative skills need to be included by the institutions that have conjoined wood construction and digital design/fabrication in their research and educational programs (see for instance the examples reported in [11], and in [12]. The Timber Tectonics in the Digital Age course is a partnership between the Oregon State University (OSU) Wood Science and Engineering Department and the University of Oregon (UO) Department of Architecture. During this course, a multi-disciplinary group of students, embodying the three roles of manufacturer, engineer, and architect, remotely work in teams to design a small-scale timber building. They use parametric modeling tools for architectural conceptualization, engineering analysis, and prototyping. The aim of this course is to develop contemporary hard and soft skills needed for AEC collaboration in the emerging digitally-driven wood industry, thus reflecting what the industry faces as it modernizes.

1.1. Purpose of the Study

The purpose of this study was to investigate what relationship, if any, exists between interoperability and collaboration dynamics within the digitally enabled multidisciplinary student design teams.

Interoperability can be generally defined as the ability of diverse systems and organizations to work together (interoperate) [13]. It is worth clarifying that the term "interoperability" is used in this study to describe digital data share dynamics among users rather than intrinsic features of a software environment.

The analysis in this study can contribute to revealing factors that can be modified to increase the quality of interdisciplinary teamwork as well as conditions to best provide digital tools to enable full engagement and prepare students for professional practice.

Research Questions

Our research questions, formulated specifically in the context of integrated parametric design, were the following:

(Q1) Are the quality and level of digital data sharing related to a project workflow, and specifically to the way members of a design team divide their tasks and coordinate their work?
(Q2) Are the quality and level of digital data sharing related to promotive interaction and knowledge construction?
(Q3) Are the quality and level of digital data sharing related to specific design decisions, such as main design drivers and moves?

To answer these questions, the amount of interoperability developed through the parametric platform used in the course was analyzed in relation with collaboration dynamics in the teams, project drivers, and design iteration outcomes.

1.2. Background

1.2.1. Tools for Digital Design Collaboration

Parametric design has been applied in architectural practice for more than two decades, and it continues to evolve as software and knowhow become available more widely [14]. Computational design initially embraced the concept of parametricism as a method for exploring new formal possibilities to represent the contemporary zeitgeist at the scales from urban design to architecture to product design [15,16]. By articulating geometric and algorithmic relationships, a robust set of related solutions can be generated, which can be evaluated against criteria to find the best solution for changing conditions.

The teaching of parametric design has grown with software development in terms of user interface, architectural representation, and output applications. User interfaces have evolved from numeric tools (i.e., Microsoft Excel) to approximate curves in Gaudi's Sagrada Familia models through generations of programming languages (object-oriented modules) to visual scripting languages such as Generative Components, Grasshopper, and Dynamo [17], to include real-time sensor data [18]. As more robust digital representations allow a more sophisticated consideration of architectural problems into performance simulation, the teaching challenge also increases.

Two main categories of parametric design tools are currently available: those based on generic associative-geometry platforms such as Grasshopper and those based on the Building Information Modeling (BIM) paradigm, where components of a building are described by parametric relationships. In both types, parametrized mathematical descriptions and associations generate a range of design variations by controlling a series of factors or parameters. With BIM software, the roles and properties of specific building construction components are developed to provide a more robust model for engineering analysis, construction planning, and facilities management. While parameters in both types of software can define properties such as material stiffness, reflectance, or insulation for building performance simulation, typically, BIM software has more robust pre-defined architectural systems, while generic associative-geometry software such as Grasshopper has a constellation of small, targeted applications. Genetic algorithms use a dynamic evolutionary process to optimize formal solutions. They instantiate a range of options and "cross-breed" variants that best meet defined criteria within a defined threshold of time or performance [19,20], i.e., Galapagos [21].

Architects and engineers use multiple design tools sequentially or concurrently, typically with a central workhorse. Technology plays a mediating role in communication and collaboration. Digital architectural design collaborations initially blossomed in the 1990s as the Internet brought together remote expertise to address complex problems. While ubiquitous social media tools now facilitate connection, successful digital collaboration still depends on how smoothly communication tools are meshed with other work processes (for design ideation, evaluation, modification, and prototyping). Despite software data exchange standards, the interoperability between software platforms requires testing and sometimes negotiation.

A common digital workspace that provides data management and communication services can ensure that all people work together on the consistent project information. This can be as simple as an online filing system with protocols for library check-out/check-in, versioning, automatic backup, artifact commenting, and online linking. Marra et al. 2016 [22] used Google Drive integrated with pedagogy components to evaluate the effectiveness of technology-enabled collaboration scaffolds to support students enrolled in an undergraduate industrial engineering course in their design tasks and enhance the effectiveness of collaborative learning. The study found a positive correlation between the use of the collaborative environment and improved student learning outcomes.

In particular, the use of epistemic scaffolding, in the form of prompting questions to guide the students in the tasks required in each project phase, was highly correlated with project grades [21].

Parametric design tools, such as BIM tools, can support more complex collaboration tasks, such as identifying and resolving conflicting representations (clash detection). In a federated model, independent actors can work separately on different aspects of a building model that can be accessed together as a composite 3D model, as opposed to one large file, which might have chunks located in virtual space with individual permissions for library check-in/check-out protocols.

Finally, computation can support AEC information exchange and decision making through interactive visualization. For example, [23] created a Design Space Construction Framework to visually map building performance metrics across iterative design variations. By graphing each building performance factor's impact (i.e., energy, daylight, cost, carbon emission rate) along with stakeholder preferences (values), it clarifies the costs and benefits of each variation. Barring a common digital platform, file standards and translators provide critical means for bringing together contributors. Preidel et al. [24] explained how commercial and university projects supporting collaboration through a cloud-based model server led to Britain's Common Data Environment (CDE), the publicly available specification PAS 1192, and then ISO 19650 in 2018–2019. This kind of robust data exchange standard for building information models facilitates interoperability between participants using different software tools for different purposes.

1.2.2. Digitalization and Integrated Design in the Wood AEC Industry

Digital tools are starting to affect every aspect of the AEC industry: component production, architectural design, engineering analysis, construction methods, and building operations. A European research project completed in 2017 analyzed the state of the wood AEC industry with regard to the adoption of digital tools, and more specifically BIM, in integrated design practices [5]. The methodological approach of the leanWOOD project was based on detailed analyses of timber construction projects with high levels of prefabrication. Despite investments of European wood industry in CNC production machinery and BIM software, findings of the leanWOOD research highlighted that cultural and organizational factors, such as scarce IT literacy and limited interoperability with upstream project partners, hindered full technological adoption and lean process implementation [25].

A progressive shift to digital platform-based design and design-to-fabrication solutions has been recently fueled by mass timber projects, which use structural engineered wood products for advanced engineering systems (e.g., [26]). The advantages of mass timber construction include a high level of prefabrication and a high precision of the as-built conditions, both of which can compress project timelines, increase construction efficiency, and lower overall costs [26]. Staub-French et al. (2018) [27] illustrate the benefits of using parametric design tools, and specifically BIM, in mass timber projects based on Design for Manufacturing and Assembly (DfMA) principles. They also present a review of several associative-geometry parametric design tools used by the wood construction industry, discuss interoperability issues resulting from data sharing across different actors in the supply chain, and point to the steel industry's phased levels of detail as a model for timber [28].

Modular, prefabricated mass timber construction requires careful upfront planning and integrated design for efficient on-site assembly. Lang et al. 2019 [29] describe the use of a parametric design approach to design a 12-storey, modular, mass timber housing project in Vancouver, Canada. The approach is based on the morphospace principle [30], which defines the range of design possibility within certain constrains, namely module sizes, setbacks of module stacks, building height, and other structural parameters. The parametric approach proved to be effective in fostering collaboration between architects and engineers [30].

The current state of practice shows the application of different parametric tools in separate phases of a building realization. Parametric tools based on associative geometry are typically used to support the fluid ideation of early design, performance optimization, and rationalization for fabrication, while the specificity of BIM components is invaluable in the later design stages to support processes such as 4D construction visualization, project coordination, and cost analysis [31].

2. Theoretical Background on AEC Collaboration

2.1. Group Dynamics in the AEC Design

Research on assessing and enhancing AEC collaboration tends to emphasize either human factors or technical innovations. Studies include controlled research exercises and analytical case studies in educational or professional settings. Similar to this paper, studies often try to understand the role of digital tools by examining the relationship between tool usage and collaboration outcomes.

Effective action can be considered in terms of motivation and ability at three scales: individual, social, and structural according to the Six Sources of Influence model [32]. Table 1 shows how this model provides a lens on what shapes group interaction and team agency. Success happens when at least four cells of the matrix are supportive.

Table 1. Factors influencing group interaction and team agency [32].

	Motivation	Ability
Personal (individual)	Individual drive	Individual skills and knowledge
Social (team)	Encouragement or peer pressure	Complementary skills and knowledge
Structural (environment)	Rewards, accountability	Enabling context

The team's work environment structures what is possible to achieve: strong collaboration tools and interoperability training are enablers. While each person brings individual drive and experience, communication tools enable partners to understand them. Strong communication makes it easier to give the support that enables individual talents to flourish or shrink. For example, feedback mechanisms such as "likes" reinforce engagement, while poor responsiveness drives down engagement. Within interdisciplinary, integrated teams, the gaps in each person's knowledge provide incentive for interacting with complementary partners.

On the social level, [33] defined key tasks performed by the members of a design team, i.e., the initial brainstorming (idea generation), the activity of co-editing (e.g., reviewing and revising a proposed solution), and the negotiation phase consisting in "deciding what should be done and who should do it" ([33], p. 403). Additional kinds of interaction can be observed in successful partnerships. Peng 1999 [34] described two alternative dynamics/phases in collaborative design: "coordination" (design change accepted by others) vs. "negotiation" (design change not accepted). The following elements of cooperative learning defined by [35] well reflect effective collaboration dynamics in integrated design teams: "positive interdependence", which defines each member's responsibility for the success or failure of the team project; "promotive interaction", which occurs when each team member facilitates each other's efforts to accomplish the team's goals (for instance, exchanging information and materials [36,37]), providing team members with feedback for improving the subsequent performance of their assigned tasks [38]; and "individual accountability". Additionally, in disciplines where knowledge capital is key, such as in ACE professions and exemplarily in the modern wood construction industry [39], co-construction of knowledge and meaning negotiation among team members characterize effective communication and collaboration [40] and are key features of an integrated design

team. In this regard, [41] demonstrated how the development of common semantics is an accurate indicator of knowledge construction and sharing within the team. In interdisciplinary teams, common vocabulary and semantics indicates knowledge construction across disciplinary boundaries.

2.2. Impact of Data Exchange on Collaboration

The various interactions in a design team mainly occur when the results of an activity are communicated through some form of data exchange [42,43], which is shaped by the structural context or working environment. According to [42], the quality of data exchanges is an indicator of the level of collaboration in a team. As a consequence, problems in data transmission, data use, and interpretation may hinder collaboration [44]. As these problems can be due to differences in computing environments, techniques, and tools used to generate and manipulate the data in different design disciplines [44], a common platform or interoperability facilitates success.

The term "tectonics" can be used to describe collaborative, concurrent design in contrast to the traditional relationship among disciplines, with separate discipline-specific design areas: structure, space, material, and technology [45]. Tectonics can be defined as the art of deploying construction technology in such a way that it forms an integral component of the architectural and structural design and actively helps to shape it [45]. A large body of literature has considered how tectonic designs are developed through the media and methods of production. Oxman (2012) [46] reframed the typical collaborative design tasks in an "informed tectonics" perspective, which is a "holistic integration of design, materialization, and fabrication" provided by digital technologies.

Parametric modeling supports a variety of design processes: the generation of a desired geometry, based on associative relations and/or topological structures; the modification, adaptation, and refinement of a designed geometry by changing model parameters; the evaluation of different parametric variations and their effect on the expected design; and design decisions based on materials, technology, and fabrication methods. According to [46], the analysis–synthesis–evaluation workflow can follow different directions depending on the driving force and digital paradigm used. Not only the sequence of the informing processes can vary, depending on the approach used, but also different types of iterations and integration of digital and material workflow are possible. As such, design ideation can be strongly related to the visual representation media [46], which are informed by material properties and structural requirements [47], driven by the production of physical and material products [48], or based on negotiation processes between digital form and structure (e.g., "digital form-finding" and "morphogenetic processes" [49]). These references drove examination of the student work for how digital tools interact with the relative dominance of form, structure, and material in the design process.

3. Method

3.1. Study Setting and Participants

This section analyzes data from the "Timber tectonics in the digital age" course, which is a class available to both advanced undergraduate students and graduate students at OSU and UO. OSU students from the Wood Science and Engineering department are either enrolled in the Renewable Materials (RM) Bachelor of Science (BS) degree program, or the Wood Science graduate program, and students from the accredited programs in the School of Construction and Civil Engineering. Students from the University of Oregon come from the accredited Bachelor Architecture or Master of Architecture programs in the School of Architecture and Environment, which is part of the College of Design. A total of 60 students were enrolled in the three iterations of the Timber tectonics course in 2017, 2018, and 2019. The number of participants from each school varied for the three years: eleven architects, two engineers dual majoring also in wood science, and two other wood science students in the first year; nine architects, four engineers with one dual majoring also in wood science, and two other wood science students in the second year; and lastly,

seven architects, seven engineers, two dual majoring in wood science, and eight wood science students during the third year.

The course was arranged in a mixed lecture and laboratory format and met for a total of fifty hours distributed across ten weeks. After an introduction, the first part of the course content was organized in a series of five thematic modules distributed over five weeks. In each module, students learned about a specific structural system (Figure 1) and applied digital parametric tools for the design and analysis of these systems. The second half of the course was devoted to the design, analysis, and prototyping of a team project.

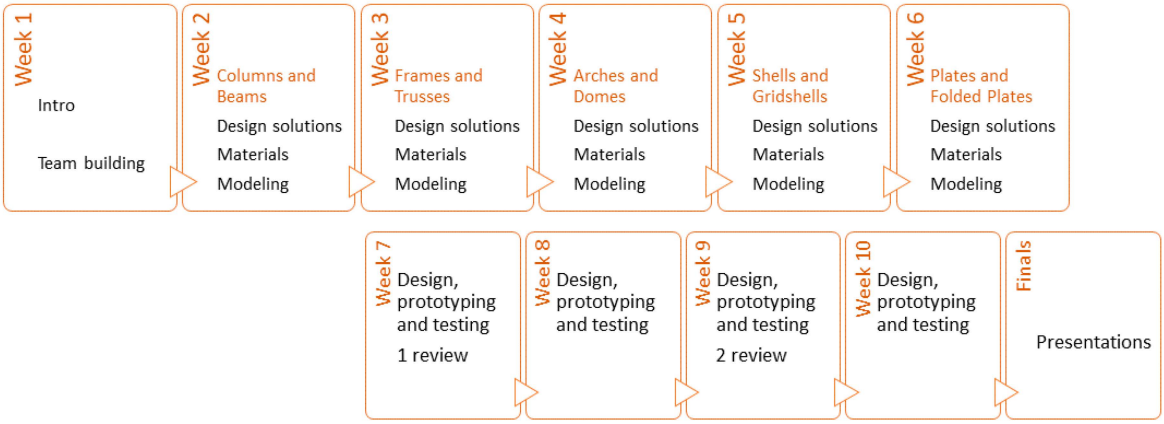

Figure 1. "Timber tectonics in the digital age" course content and organization.

Students learned the parametric design and structural analysis software through formal instruction, peer teaching, and self-study. A one and a half-day intensive hands-on introduction to parametric design was provided to those students who had no previous experience. During the first five weeks of the course, live tutorial sessions (local or remotely broadcast) provided basics of parametric modeling and structural analysis.

Most classes were delivered synchronously on the two campuses in Corvallis (Oregon, OR) and Eugene (OR); the students and the two lecturers were connected via video-conference, which was supplemented by face-to-face interaction. The class met face-to-face, as a whole, four times during the term: the initial course overview and team-building, two intermediate project review meetings, and a final presentation. During the first two weeks, students self-selected teammates based on peer interview and online profiles posted on the class blog. Self-selection was done according to rules that encourage diversity: criteria for group formation were to have at least one student from either architecture, engineering, or wood science, and include in the team a mix of undergrad and grad students. However, this was not always possible, and in three cases, groups were rearranged or aggregated after the first iteration of the design. The benefits of "constrained" self-selecting teams, instead of allocated groups, were discussed by [50] in the context of Architecture design studios.

Student teams focused on the design of a small-scale pavilion. For its design, students were encouraged to use the structural systems studied in class, showcasing the use of different engineered wood products, according to the specific structural needs. Teams found their own ways to communicate, typically using a combination of phone, text, chat or email messaging, and video-conferences, often sharing sketches and graphic data through a common file storage. The primary software tools were Grasshopper [51] and Karamba [52] plug-ins for McNeel's Rhinoceros for integrated parametric design and structural analysis. We note that other generic associative-geometry tools with the same affordances could be used for the same education purpose. Prototyping included the use of traditional wood shop equipment and digital fabrication tools such as 3D printers, laser cutters, and computer numerical control (CNC) machines.

Architects, engineers, wood products manufacturers, and fabricators participated in the class by providing project feedback to students, during the review meetings and the final presentation, and through invited talks.

3.2. Data and Data Collection

This educational experience yields data from looking at student work and feedback. Data include textual documents (i.e., entry and exit self-assessment, team evaluation, reflections on team projects and review critiques, feedback on the course) as well as visual documents and artifacts generated by the students. The course was launched in 2017, and three years of data have been collected so far and presented in this paper. Note that data from the 2020 course iteration are excluded from this study due to the substantial didactical changes made, partially as a response to the COVID-19 pandemic but also as a consequence of the lessons learned from this study (see Section 5.3).

Data types are summarized in Table 2. All the students had an opportunity to self-assess their entry skills (Dataset 1) as well as the skills and knowledge acquired during the course (Dataset 5). Datasets 2, 3, and 4 describe the different phases of the team project and include both student text entries and visual data (student's artifacts, comprising hand-sketches, digital models, graphics, and physical prototypes). At the end of the term, students could submit an evaluation of the course and how it addressed learning goals (Dataset 5). In these final reflections, students were also asked to assess team performance and peer contributions. These data were collected through the course blog and an online learning management system.

Table 2. Qualitative data and data sources.

Dataset #	Type of Data	Description	Examination
1	Textual	Prior knowledge and learning goals/interests Entry level self-assessment Blog interviews	Self-assessed prior knowledge and team composition
2	Textual Visual	Team project 1st design review	Collaboration and workflow dynamics
3	Textual Visual	Team project 2nd design review	Collaboration and workflow dynamics
4	Textual Visual	Team project final presentation	Collaboration and workflow dynamics
5	Textual	Course evaluation and final reflections with team assessment	Collaboration and workflow dynamics (triangulation)

Data from dataset 1 were used to describe team compositions (discipline and self-assessed skills and experience of each team member). Datasets 2–4 reveal the design drivers and incremental design development. Datasets 1 and 5 were also analyzed to evaluate students' perceptions of integrated design and how they changed after the course.

A table in the "Supplementary Material" lists questions that were administered to each student at the end of the course to evaluate the course experience and teamwork, along with the factors that were analyzed in this study (Table 3). The students' responses to these questions constituted "dataset 5" (Table 2). These data were used to triangulate data extrapolated from each team's reflections submitted after each design review and the final presentation.

Table 3. Analysis factors for examining student work.

Codes	Sub-Codes
Positive interdependence [35]	a. Sequential division of tasks b. Concurrent division of tasks
Accountability [35]	c. Loosely coordinated, members' contributions are redundant or missing d. Highly coordinated, equal share of work
Promotive interaction [35]	e. Scarce promotive interaction f. Effective assistance [53,54] g. Information exchange [36,37] h. Constructive feedback [38] i. Challenging each other's conclusions [55] j. Exploring different points of view [56]
Construction of knowledge [40,41]	k. Within disciplinary boundaries l. Across disciplinary boundaries
Digital data sharing	m. Good interoperability (smooth data flow from parametric models to other data types to advance analysis and design) n. Poor interoperability (parametric models isolated from other aspects of the design/analysis development)
Tectonics drivers	o. Material- and structure-driven (informed by material properties and structural requirements) [47] p. Material- and fabrication-driven (driven by the production of physical and material products) [48] q. Driven by digital form-finding r. Based on negotiation processes between digital form and structure
Design moves	s. Small incremental adjustments t. Radical design shifts

3.3. Concept Measurement and Analysis

Data were analyzed qualitatively using both narrative and content analysis. Narrative analysis was used to identify the use of language in textual documents, in particular to evaluate collaboration dynamics within the interdisciplinary teams such as co-construction of knowledge (for instance, development of a common semantics and jargon), the division of tasks and workflows (e.g., sequential vs. concurrent), and the forms of promotive interaction (Table 3). Content analysis of visual data was carried out to evaluate types of data sharing, main drivers of the tectonics design (e.g., structural requirements, fabrication constrains, digital form, or a negotiation among those criteria) and design moves (e.g., incremental vs. radical shifts) (Table 3).

An iterative hybrid deductive–inductive method was used to generate a research-based list of measures of collaboration and workflows and refine it to address the study objective (Table 3). The coding generalizes complex processes into an abstract summary to reveal relationships between formative factors and outcomes. Bias subjectivity of faculty/observers is considered in the assessment process. Validation is achieved by triangulation, i.e., incorporating multiple sources of data and involving both instructors in the coding tasks.

Among the "Six Sources of Influence" [32] elements described in Table 1, the use of digital design tools is a "structural ability", or an enabling context, that was used as a lens through which to analyze other elements of the team work.

Reflective writing revealed the more hidden aspects of teammate interactions (interdependence, accountability, promotive interaction) as they evolved with each deadline (datasets 2–5), especially in the final reflection. The design project graphics (datasets 2–4) left a trail of authorship that supported the textual data and revealed the construction of knowledge, digital data sharing, tectonic drivers, and design moves.

4. Results

4.1. Prior Knowledge and Team Compositions

Analysis of the entry-level self-assessment and the data blog interviews (dataset 1 in Table 2) showed they brought greatly varied backgrounds. The data showed that while the architecture students had a range of previous experience with parametric design and digital fabrication, none of the wood science and engineering students had exposure to those tools and processes prior to this class. A high percentage of architecture students were familiar with light wood framing and structural systems, from previous or concurrent coursework in building construction, structural analysis and/or timber design. Only a few engineering students claimed knowledge of wood properties and products. Almost all wood science students claimed superficial knowledge of structural systems.

Some teams had members with blended expertise, for instance, dual major students in wood science and engineering. Based on self-evaluation data, all the teams in the second and third year of the course had a well-balanced distribution of expertise, while during the first year, architects outnumbered the other disciplines.

4.2. Data Interoperability, Workflows, and Collaboration Dynamics

In the following section, course data are analyzed to address our research questions. Correlations between interoperability, collaboration, and specific workflow factors are discussed from the analysis of the first and second design review submissions and the final presentations (datasets 2–4).

Figure 2 shows the frequency of different team dynamics developed during the course and quality of data sharing.

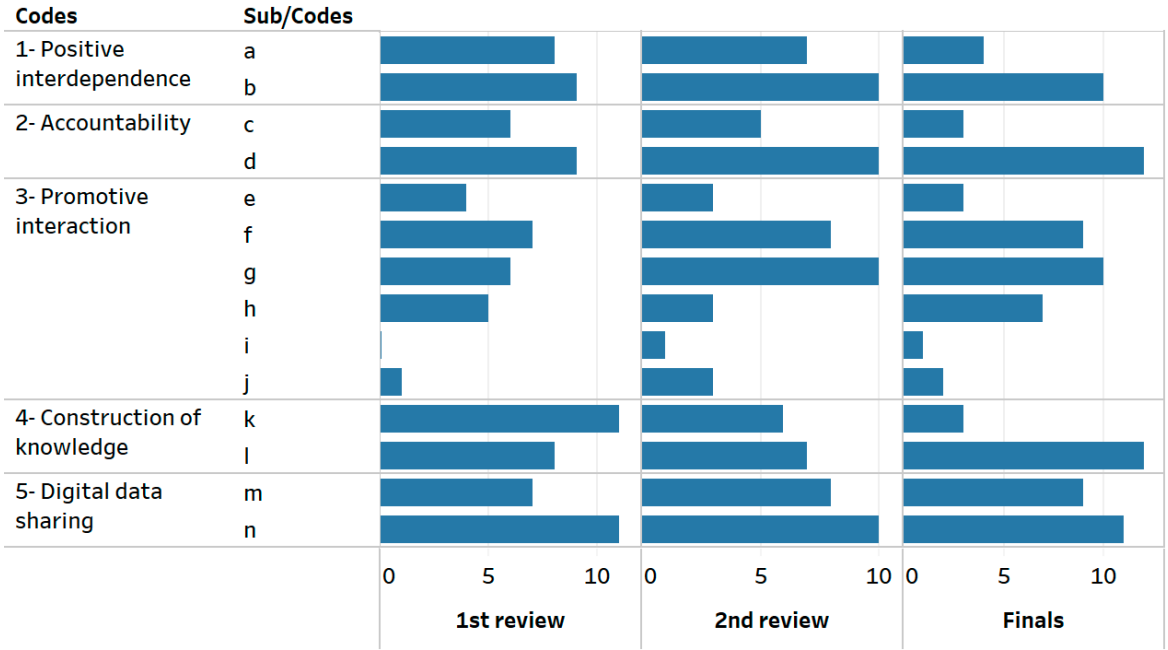

Figure 2. Frequency of collaboration dynamics during the term (from the 1st design review to the final presentation).

It can be observed that while cases of poor interoperability persisted throughout the term, there is also a slight increase of smooth data flows from the first design reviews to the final presentations.

Students generated and shared data from the parametric models ranging from 3D visualizations to outputs of the structural analysis, such as stress, deformation and utilization maps, and, in limited cases, to 3D models for digital fabrication and prototyping.

Good interoperability was characterized by smooth data flow from parametric models to other data types to advance analysis and design. This type of workflow could consist either in a coordinated use of different plugins of the software package to perform various project tasks or by the use of the parametric model for preliminary design and then exporting the model out for refined analysis, fabrication, and presentation. In contrast, poor interoperability was characterized by a disconnected use of alternative ways of design representation and analysis that was neither based on outputs from the parametric model nor functional to its development.

From the analysis of data generated throughout the different submissions and the course years, it appeared that the quality of interoperability varied among team interactions. Good interoperability was apparent for some workflows (for instance, from form-finding to structural analysis) but not in other tasks (for instance, from the overall design to the definition of the construction details). This explains why some cases of poor interoperability persisted also during the last phases of the team project.

Results in Figure 2 showed an increase of concurrent design tasks toward the end of the term. A higher number of sequential division of tasks at the beginning of the collaboration was due to the fact that many teams started with loosely coordinated brainstorming, which led to an initial design idea. One student in the team would be in charge of developing this idea as the initial parametric model, and they would share the data from the model to other components of the teams. A steady improvement in terms of coordination (i.e., accountability) is also evident from the data and positively correlated with a reduction of sequential tasks.

A consistent and general increase of promotive interactions occurred during the course, with more information exchanged after the second half of the term. While students considered exploring different points of view especially during the second design iteration, constructive feedback was exchanged particularly at the beginning and at the end of the design process. This can be explained by the fact that the tasks requiring inputs from different experts in the team increased with the second design submission, and this sometimes led to reconsidering early design decisions. It is worth noting that in a few isolated cases, promotive interaction occurred by challenging teammates' conclusions, also in this case, starting from the second design submission. As expected, construction of knowledge occurred initially more within the disciplinary boundaries and progressively expanded beyond them to include many interdisciplinary elements covered in class and brought by the team members.

The following sections discuss the impact of interoperability on the various aspects of design and its overall impact on the collaboration by triangulating results presented in Figure 2 with student's final reflections on the course and their teamwork (dataset 5).

4.2.1. Conceptual Design Thinking and Parametric Modeling

An interesting aspect related to digital data production and sharing is how the use (or not) of the parametric tool during the early design conceptualization impacted subsequent workflows and design moves, as eloquently described by one of the architects' reflections:

> "As with any design course, I feel that initial design iterations ought to be conveyed by means of sketches to organically and quickly export these fresh ideas. Moving to the computer should happen as the idea is solidifying but now more than ever I feel it is imperative to have some sort of raw version of the idea in the computer so that it could be run through the physics checking software. In addition, designing (with the parametric tool) in general it is good to be started

> sooner rather than later because thanks to its parametric controls such as sliders and toggling buttons it is made to be easier to understand just how quickly the entire design can change when just a small fraction of it [is] tuned up or down."

The translation from hand sketches to parametric model sometimes reinforced and refined the design idea, (e.g., "[the engineer] would send me sketches [of the connections] and I would digitize it, and in re-designing it in the computer, I would get a better understanding of how it worked by questioning its shape and placement", "We also realize some details were not considered in the sketch but were noticed thanks to the conversion [into the parametric model], like connections and load behavior, as well as some parametric issues like the angle in the roof support in order to achieve the desired structure optimization"). However, in other cases, the conversion into the parametric platform represented a roadblock in the design process ("An example of this would be the architect's first sketches for the pavilion design, they were almost impossible to design [with the parametric software] and to apply the correct loadings in the beams ... "). Beginners had difficulty seeing whether a design concept could be parametrically modeled as they were still learning the software's capabilities.

4.2.2. Interoperability and Structural Analysis

Engineering students preferred most of the times to use external finite element analysis software and hand calculations to complete their structural analysis. Factors for this choice ranged from the limited trust to limited knowledge in the capabilities of the parametric tool, "I know that [the engineer] had to use other programs to evaluate our structure, whether this was due to the limitations of the program, or his lack of experience with the program, I am not sure", "During the later parts of the course, I opted to transfer the parametric model to another software, which I was more familiar".

However, the translation from a conceptual form to a design that could be developed and analyzed throughout was not always straightforward: "There has never been an issue designing the structure and agreeing on a design, but compiling those alternatives to a digital model and making sure the analysis is done accordingly was very difficult."

A potential pitfall of the digital design process, and associated difficulties of structurally analyze complex parametric geometries, was captured in the comment of one of the engineering students:

> "As we've progressed further into parametric modeling, something that has begun to stand out is the potential pitfalls of complexity. Parametric design/analysis creates a very collaborative and highly creative process ... which can lead to extremely abstract and complex design. However, with that difficult geometry comes unique loading patterns and even more complex stability-based failure modes."

4.2.3. Interoperability for Prototyping

Cases of good interoperability were for instance when the fabricator in the teams could convert the parametric file into CAD (computer-aided design) files and further work on construction details to streamline the file-to-fabrication process: e.g., "The digital file-to-fabrication has offered some opportunities to streamline the project development process. The example that comes in mind from our own project is how connections were 3D-printed directly from the parametric files prior to the second review."

However, this was not always the case, and poor interoperability occurred when CAD/CAM (computer-aided manufacturing) files were generated from scratch (or from hand sketches), sometimes showing clear discrepancies with the parametric model, "I made a big mistake with the model construction, in that I neglected to import the [parametric] file into [the CAD/CAM software] for CNC and laser use (...) The result of this was a half-complete pavilion and a lot of wasted money on materials," or when the model was not functional to the development of the construction details, "Throughout the course, an aspect that I feel I did not quite fully explore and gain an understanding of is the creation

of architectural detail through the use of the parametric design tools. I am not sure if it was my lack of understanding of the program or the simplicity of the program itself, but the understanding of the connection requirements and how to achieve this was not very clear"; "As our team was new to the software, we did not have time to develop a refined assembly plan and fabrication details through the design software, and ended up creating a separate drawing for the required module pieces."

4.2.4. Correlations between Interoperability and Collaboration

In terms of the collaboration dynamics established in the teams, a good correlation was found between the type of data sharing and both positive interdependence and accountability. As it can be observed from Figure 3, teams with strong interoperability were able to coordinate concurrent work, and they showed high coordination with an equal share of work. Conversely, cases of poor interoperability were more frequently characterized by a sequential division of tasks and poorer coordination among team members. It is worth noting that teams with weak interoperability began with more independent, sequential work, although once the design direction was established, they could work in a more coordinated, concurrent fashion.

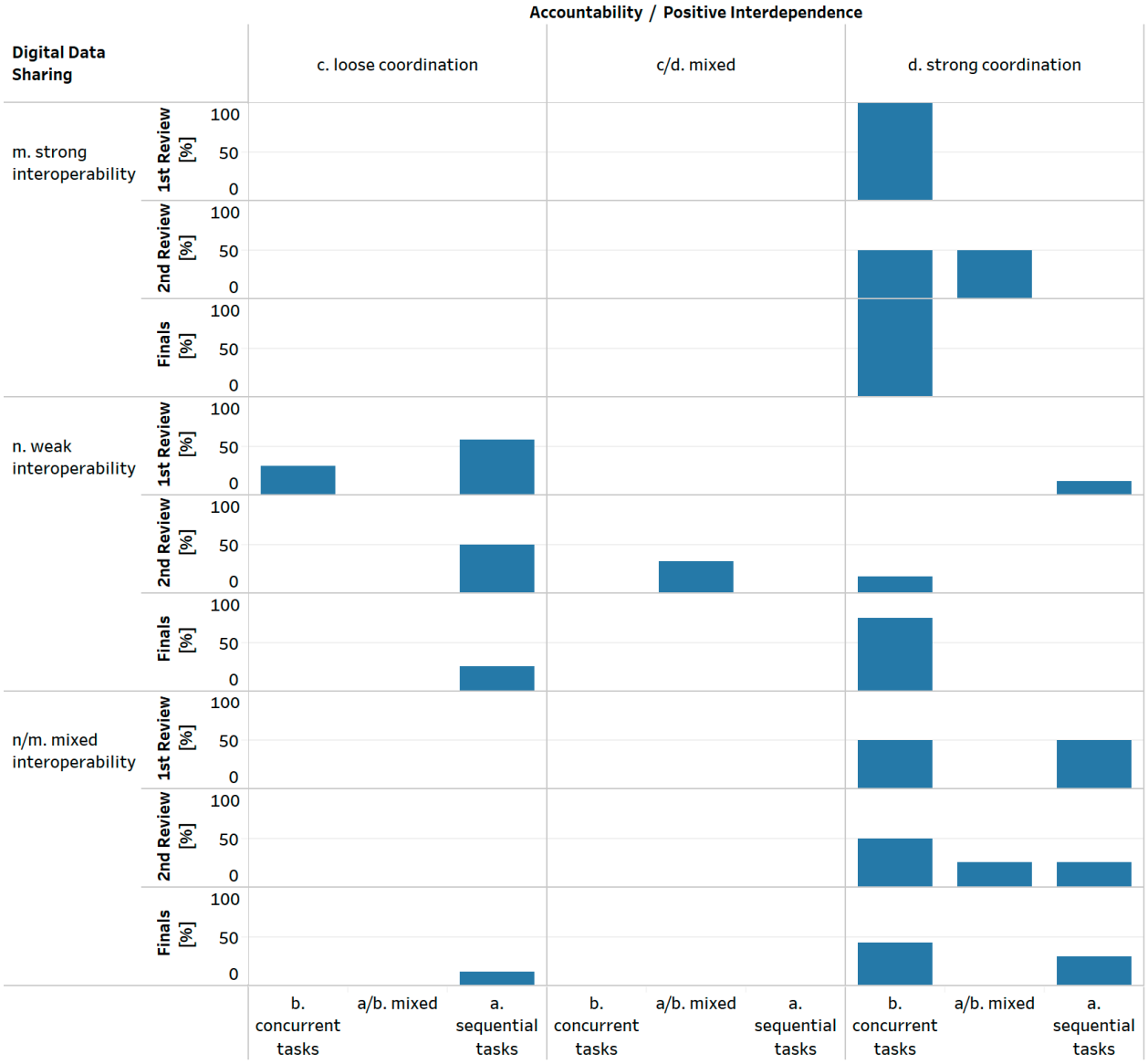

Figure 3. Relationship (expressed in percentage of code frequency) between digital data sharing, accountability, and positive interdependence.

In particular, data were analyzed from the perspective of the type of interoperability enabled by the design/analysis/production media, and its relationship with team dynamics, types of design iterations, and the integration of digital and material paradigms.

As shown in Figure 4, in case of good interoperability, promotive interaction occurred prevalently through both effective assistance and information exchange (e.g., one student reported, "If one of us had some trouble, he was always reaching for help to the other members of the group"), often in concurrence with the exchange of constructive feedback, and occasionally bringing team members to challenge each other's conclusions and explore different points of view. This frequently led to the construction of knowledge across the disciplinary boundaries of each team member and to an expansion/consolidation of discipline-related knowledge.

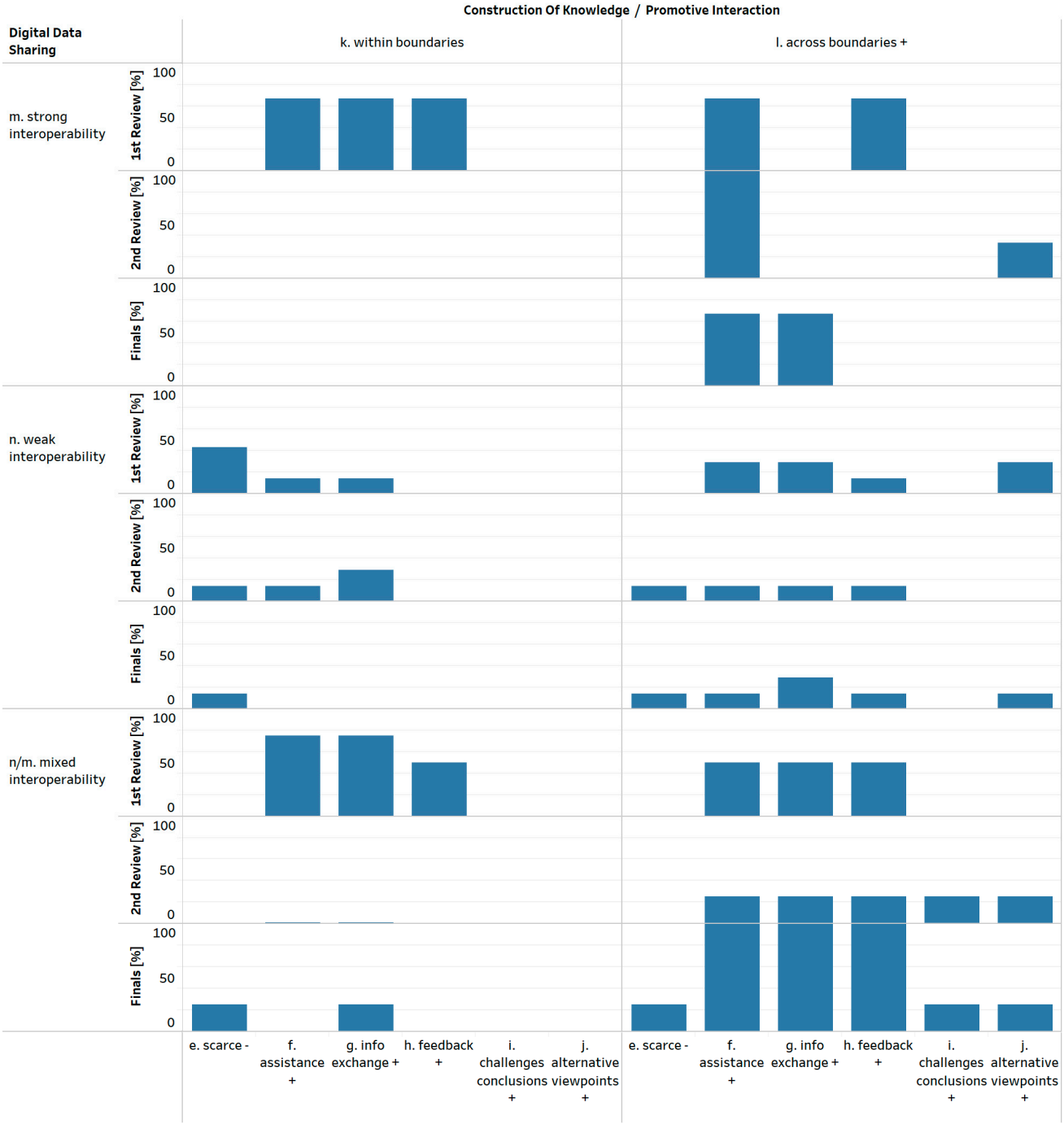

Figure 4. Relationship (expressed in percentage of code frequency) between digital data sharing, positive interaction, and construction of knowledge.

Figure 4 shows that when data interoperability was poor, promotive interaction was often scarce, as also reported in the final reflections (e.g., "the reality is that the designing stages didn't seem very efficient and the designs were constantly changed throughout the entirety of the term, making it hard to develop the full potential of any one design"; "The biggest challenge for me, I think, was to get my partners to listen to my ideas. I had moments of disappointment when I would work for hours on connections details and they would not take them into account or change completely the design").

In some cases, interoperability challenges and the choice to resort to another media type promoted the exploration of different points of view: "We learned that although the model may work on the screen and in the digital file, that doesn't mean it's the best or the most feasible way to make it in the shop. As [the fabricator] learned, it was easier to have two separate pieces for the module to reduce the overall height and allow for easier bending. This is something that we would have probably never have known in the digital model because in the file we aren't actually dealing with the material in real life."

Good data interoperability promoted the construction of both interdisciplinary and within-discipline knowledge. A positive correlation between good data interoperability and the construction of interdisciplinary knowledge was demonstrated by the fact that teams that improved the consistency of data sharing throughout the term (as demonstrated by codes changing from "n" to "m", meaning from poor to good interoperability, or to mixed interoperability "n/m") were also characterized by an increasing interdisciplinary knowledge. No significant differences were found in the findings presented in this section between the first year of the course, with a majority of architecture students, and results of the following two years.

4.3. Tectonics Drivers, Design Moves, and Data Interoperability

The driving consideration behind the initial tectonic pavilion design—visual form, structure, or material fabrication—had a large influence on the types of design revisions. How these factors and data interoperability changed team dynamics throughout the project's development was analyzed, as shown in Figure 5.

In projects that were strongly material and structure driven, the design immediately met key criteria, so design moves were typically characterized by small iterative refinements of the initial idea (e.g., Figure 6), as exemplified also in some reflections of engineering students, "My group worked deeply in this aspect by analyzing different connections in order to find the most appropriate one considering cost and structural efficiency, different geometry options by iteration within the structure's parameters"; "Our initial meetings shaped the way to have a simplistic design of portal frames since they are structurally stable and easy to construct. Later on, [the architect] worked on aspects of orientation of structure focusing on creating functional space and overall appearance. At the same time, I was working on structural analysis, element cross-sections to provide insights [to the architect and fabricator]. Once the initial design was finalized, [the fabricator] provided feedback about difficulties in construction and connections. After suggestions from [the fabricator], we again worked to revise our design."

When the project was started from a visual metaphor or digital inspiration with complex geometry (e.g., Figure 7), radical design shifts consistently resulted as the students tried to address stability and constructability problems. In some cases, when no strategies other than the digital modeling and parametric design were used, unresolved material, structural, and fabrication issues persisted, despite the multiple design alterations. This coincided also with poor interoperability throughout the project as can be observed from Figure 5.

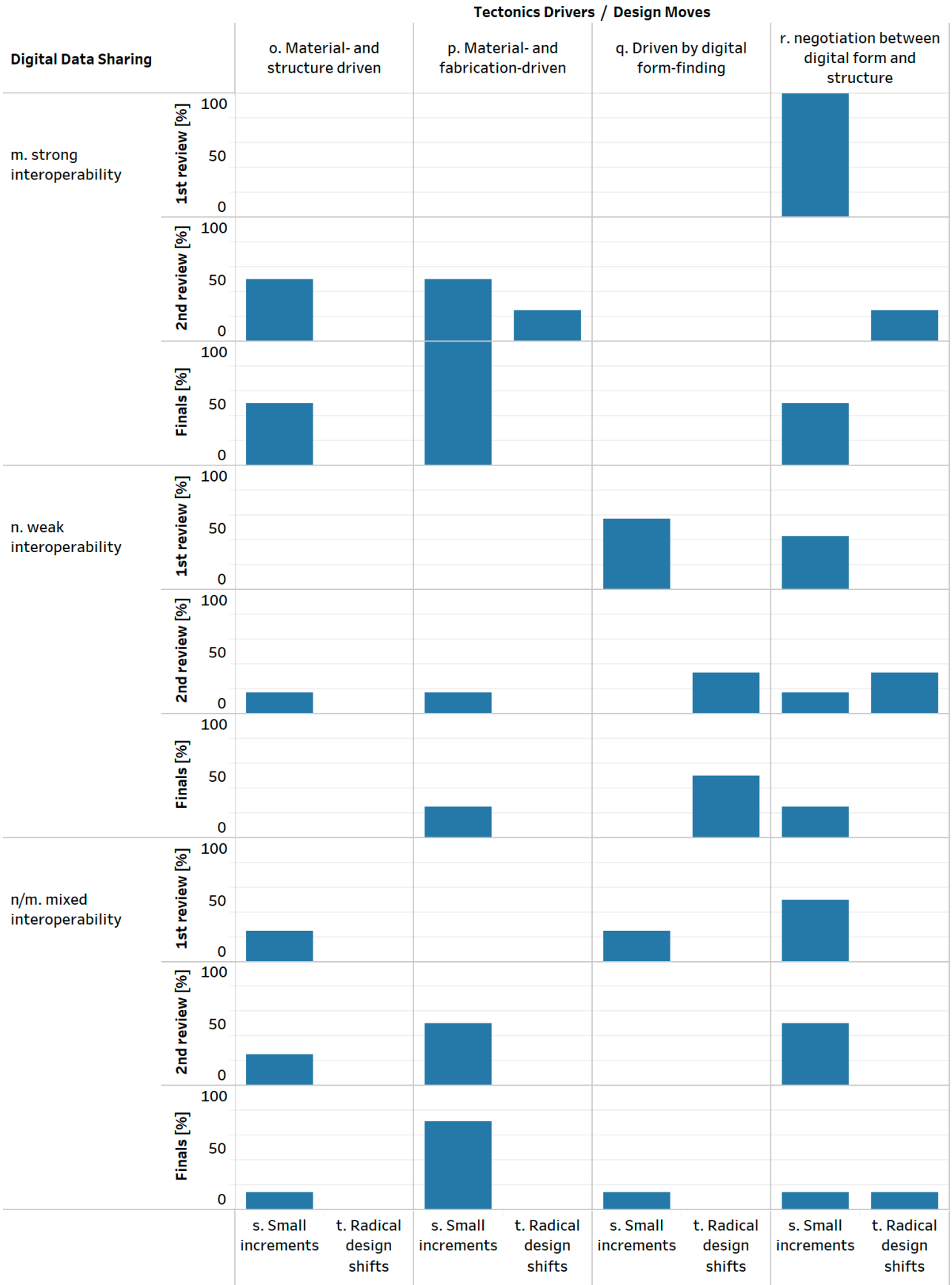

Figure 5. Relationship (expressed in percentage of code frequency) between digital data sharing, tectonics drivers, and design moves. Radical design shifts correlate with projects driven by digital form-finding.

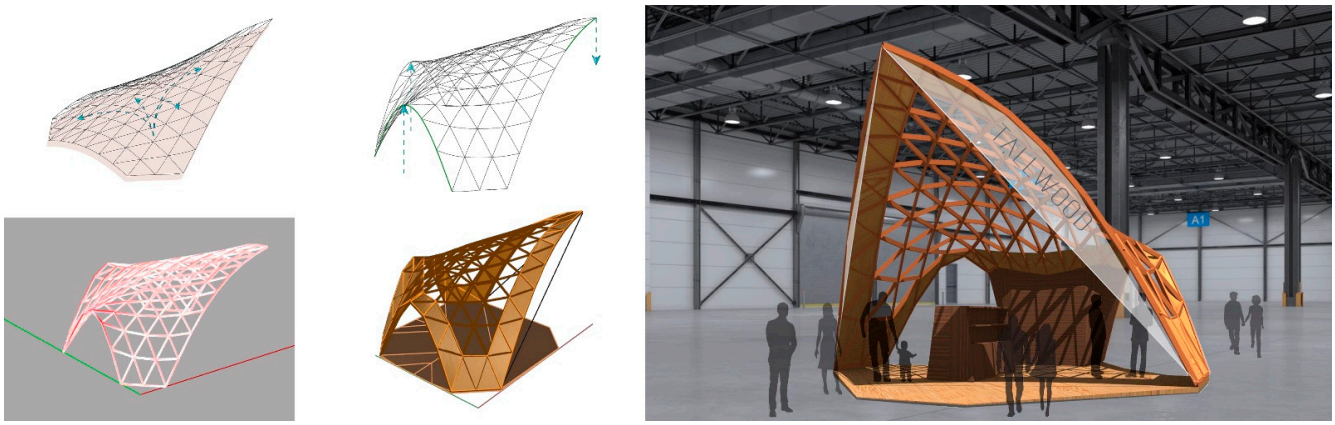

Figure 6. Example of an incrementally developed tectonic project.

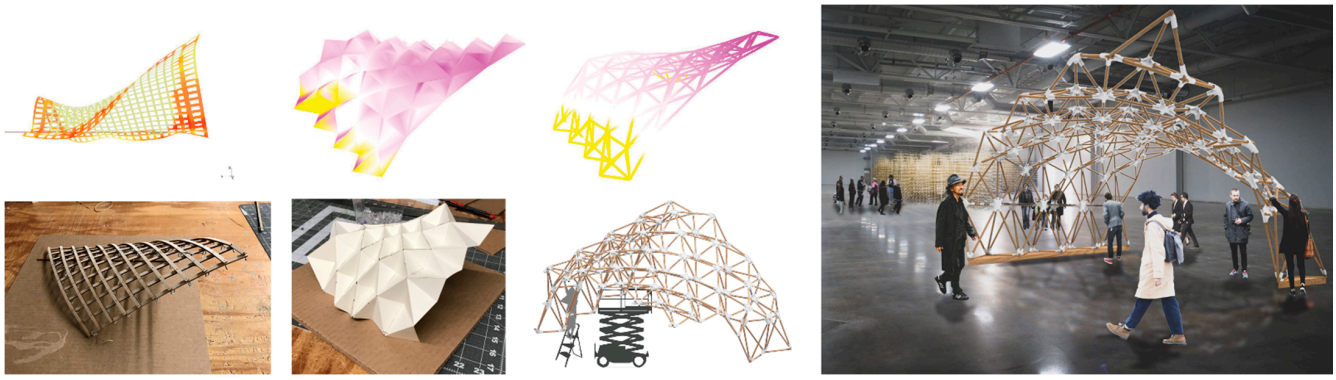

Figure 7. A pavilion project that experienced radical design shifts.

As reported in a student's reflection: "We also learned that though the concept of the wooden material forming from and returning to the earth was appealing as a concept for our pavilion, and that (. . .) the fluid form (. . .) itself as it was depicted would make it extremely difficult to construct and to engineer".

As the term progressed, all teams needed to address material and fabrication procedures, giving them more social motivation for interaction. As they worked together longer, they demonstrated greater coordination, more promotive interaction, and more cross-disciplinary knowledge sharing. Those whose workflow was characterized by good data interoperability or progress from poor to good interoperability had the most seamless ability to demonstrate competency in material and fabrication requirements. In some designs initially driven by the digital form, data-sharing roadblocks arose in the file-to-fabrication process, and students had to resort to alternative physical prototyping and testing (without relying on outputs of the parametric model) to address material and constructability requirements: "I now know that more time is needed for experimentation and testing before going all in with a plan. We put a little too much trust in the plan we came up with not knowing that it would be much more complex than it looked. I will definitely be more observant of our plans and do more small-scale testing before deciding on a full plan".

For those who started with a virtual image, incorporating early physical prototyping provided an iterative negotiation with the digital model (Figure 7), creating a smoother workflow than those that addressed material aspects later, as described in this reflection: "From my experience, this class was more of a reaction thought process rather than a think ahead situation. We would work together and deliberate until we came to a final design

that was stable and looked good [on the computer], and then began thinking of the types of joints and connections would be most efficient to make the model realistic." The challenge of building models together established trust and understanding among team members.

To summarize, the initial design motivator influenced the kind of communication required. When teams began with the structural and material basis, they established a design direction that would require only small refinements, and less taxing communication. When teams began with visual inspiration without a structural example, they often needed to radically change the design concept and were required to frequently negotiate the path forward. Because physical prototyping helped them address the structural and constructability issues and very directly communicate design intentions without worrying about digital interoperability, it led to productive design development.

5. Discussion

This study illustrates challenges and potentials of interdisciplinary/inter-institutional educational initiatives in the AEC sector, as reflected in the observed educational setting. It also provides lessons useful for all digital design collaborations. Factors affecting the quality of interdisciplinary teamwork, more specifically, collaboration dynamics and workflows enabled by digital data sharing, are discussed, as well as possible strategies to support effective design collaboration. This section is structured to discuss first lessons learned from this study, then reflect on relevant recommendations, and finally illustrate examples of implementations of these recommendations in next iterations of the presented course.

5.1. Lessons Learned about the Impact of Interoperability on Collaborative Workflows

The quality of communication, including data interoperability, proved to be key to overcoming barriers of physical and disciplinary distance. As an important communication method, robust data interoperability increases the ability to accurately transfer ideas between domains, supporting the coordination of sequential and concurrent work.

The analyzed data revealed that the ability to share ideas through strong interoperability enabled greater engagement of team partners, fostering more social motivation for team success. When information transfer was more challenging, it created an imperative for communication. For example, members needed to communicate when trying to interpret their partners' ideas into different media (i.e., translating a sketch into a digital model or building a physical prototype from a digital model). This created opportunities for promotive interaction, but it required effort to overcome challenges such as unfamiliar vocabulary as well as different values and procedures. This is consistent with Evans' 1997 [57] observation that changing media forces additional development. From our study, we concluded that the greater range of integrated media, the wider the range of considerations and the more depth of development. This may suggest that instruction could effectively leverage student's prior knowledge of other digital tools and media to facilitate data sharing.

It is worth noting that other factors enabled collaboration and counterbalanced poor interoperability in some cases, as it can be observed by examples of teams showing an increasingly collaborative interaction toward the second half of the term, despite consistently struggling with data sharing. This suggests that while organizers can promote and support interoperable data-exchange paths for moving forward, each group will find its own unique way of working together to meet requirements. When individuals prefer to rely on familiar tools and workflows, rather than invest time in developing new skills, their teams need to work around poor interoperability by coordinating independent work.

In parallel, independent work discourages holistic thinking, because every software tool prioritizes specific operations, so each person's choice of a different primary workspace software de facto devalues the other approaches to the enterprise. For instance, while transferring the model to the finite element modeling (FEM) tool empowered the engineering student to take control, it removed the analysis from the streamlined integrated collaborative parametric model. The incompatibility of different digital platforms magnifies the myopia supported by discipline-specific platforms and work methods.

Furthermore, team members generally do not see other more effective team interactions because each team primarily interacts only with itself, and a team's own inefficiencies remains invisible [58].

Specific to the ubiquitous involvement of digital technologies in contemporary design education is also the potential risk of lack of materiality awareness. In this timber design collaboration, alignment of the initial design driver with the ultimate material properties as well as structural and constructability requirements dictated the smoothness of the team project design workflow. In this study setting, especially the prototyping phase showed the "bi-directional dependency" of work and information flow [59] between designers and fabricators and the risk of disconnect between physical and digital design, material testing, and manufacturing. Narrowing the separation between virtual and material realms in design workflows is still considered a research problem [60].

5.2. Recommendations for Shaping Effective Digitally-Enabled Interdisciplinary Collaborations

Themes and patterns observed in the studied setting are generally transferrable to other educational and professional collaborations requiring an integrated design approach. The following recommendations are especially applicable for collaborations that integrate qualitative requirements (for instance, what Schultz et al. [61] referred to as qualitative spatial and qualitative temporal reasoning (QSTR)), quantitative requirements (for instance, structural performance and energy-efficiency), and physical production requirements (i.e., material and fabrication constraints).

Improving digitally enabled teamwork requires addressing individual, peer, and context factors [32] so that the situation enables and motivates individuals to do their best. Requirements for individual technical skills have been steadily increasing and therefore underline the importance of training. Engaging with quantitative design objectives (e.g., structural analysis) early in the design stage is key in emerging performance-based design practices [62], so AEC educators should consider this new industry approach. Alalouch (2018) [63] stressed the importance of introducing parametric design thinking from the early stages of design education to break down a persistent siloed nature of education, allowing students to develop a comprehensive understanding of various design requirements (i.e., qualitative and quantitative, including production constraints) and helping them achieve design goals by using computational principles. Supportive instruction through tutorials and automated feedback as in game scenarios have been shown to increase accountability, engagement and enjoyment in K-12 settings [64] and could be further explored in high education settings as the studied course.

As collaboration requires both technical means and human motivations, training can improve "soft" interaction skills, such as listening, cooperatively questioning, and negotiating conflict [65], which are needed for effective digital collaboration. Without the social motivation of needing each other's complementary expertise, it is unlikely for individual abilities to flourish. When asymmetric talents create self-sufficiency in a subset of the group, as in one person or a pair being able to solve the whole problem, it detracts from positive interdependence and reduces the motivation for promotive interaction. For positive interdependence, teammates need to see how each partner's role is crucial to the success of the enterprise [66]. If the teams are initially asked to use a variety of skills on a very simple problem, they can develop confidence for more complex scenarios later. Varied deliverables (i.e., graphic, quantitative, written, constructed) draw on different kinds of strengths, allowing each "expert" in the team to shine. Staging a sequence of varied deliverables forces the team to transition the idea through different representations, which provides a broader understanding of the design. While structuring project development through a sequence of required processes can be productive for the less experienced, it needs to be carefully planned as so that it does not overly restrict creativity [67].

Collaboration requires a supportive project delivery environment to flourish. In professional practice, each team must establish the means to robustly share and negotiate ideas by finding a common work platform, creating communication backups and piloting strong

data interoperability. In the classroom, instructors can scaffold this process by providing accessible collaboration tools, as learning to share information in the cloud prepares AEC students for professional practice [68]. The more participants share information, the more investment they have in the project and the more trust is extended, so practice in using collaboration platforms supports promotive interactions [69]. In addition, shared inter-team online collaborative workspaces allow mutual visibility not only of the team products but also of their work process.

Since feedback obtained from material and structural testing offers ways to create intuitively embodied experiences for architectural designers, interspersing physical prototyping can enrich digital workflows [61]. This is confirmed by other experiences, where an integration of hands-on fabrication, i.e., woodwork detailing, into civil engineering instruction enhanced learning of structural analysis and the use of structural modeling software [70].

While these ideas come from AEC collaboration, the observations are relevant for any digital pursuit that brings together aesthetic design, measurable performance, and physical fabrication. Project teams can only take advantage of computation's ability to examine many solutions when the whole team fluidly shares digital data. Without interoperability, software's great power of flexibility is lost. As solving complex problems requires interdisciplinary perspectives and data-centric solutions, creating robust, effective collaborations will only increase in importance.

5.3. Implementating Recommended Practices

This study confirmed the crucial role of interoperability in digitally enabled design collaborations. The study also led to reflections on the importance of complementary factors at the personal, social, and structural levels [32]. The resulting recommended practices have been incorporated in the redesign of the "Timber tectonics in the digital age" course for the Fall 2020 fourth iteration (Table 4). Our universities' pandemic response provided us with a more robust infrastructure for remote collaboration.

Table 4. Practice implementation in the "Timber tectonics in the digital age" course.

	Intervention	Improved Ability
Personal (individual)	- Training: Lecture and tutorial videos + live instructor feedback (flipped classroom) * - Increased lab time for physical prototyping	Individual hard skills
Social (team)	- Peer mentoring: Ask an Expert forum * - Collaboration training *	Promotive interaction Interdisciplinary construction of knowledge
Structural (environment)	- Use of a collaborative online workspace and digital whiteboards for communication, data sharing and presentations *	Positive interaction Trackable accountability Digital data sharing

* intervention implemented since the fourth iteration of the course (fall 2020).

The choice to deliver the course in a hybrid format, combining pre-recorded material with live interaction, is believed to increase opportunities for both individual training of hard skills (for instance, multi-domain digital and design literacy, as recommended by [63]) and soft skills supporting promotive interaction [71].

Pre-recorded video lectures and tutorials accessible from the online learning management system, covering both basic and advanced contents and techniques better support the growth of individual abilities. They also enable students to choose personalized training paths by setting the pace of the training and selecting the instructional material that better fits their learning needs [72]. In addition, the hybrid model provides more class time for instructor feedback and team interaction.

To support the development of social abilities, collaboration training sessions introduced in class prompt students to reflect together on strengths and hindrances to their collaboration, as recommended by Tran [65]. To create social motivation, promotive interaction, knowledge sharing, and collective knowledge building, we have opted to scaffold peer mentoring dynamics by setting up an online discussion forum that requires students to ask and answer questions, communicate, and articulate their knowledge to support the learning of others. The "Ask an Expert" forum also provides an opportunity to develop critical inquiry and reflection skills by formulating questions rather than just responding to those posed by others.

To provide robust infrastructure, collaborative online workspaces and digital whiteboards complement video-conferencing and the online learning management system. The collaboration spaces and whiteboards enhance communication and data sharing within and among teams by providing a vivid trail of both textual team messages, graphic weekly summaries, and digital file sharing. These allow instructors to more closely monitor workflows and team interactions, and the digital whiteboards also permit the interactive participation of external experts during online review sections.

For future research, questions that remain include how much of the team project workflow is best pre-defined as opposed to being created by the team members themselves (for more ownership). Given the limitations of any individual's perspective, how can we best support teams to have strong complementary abilities? Rather than pushing all participants to learn one common tool, how can we jump-start the successful use of common data exchange platforms that enable idea sharing without loss of information?

6. Limitations

Several factors limit the ability to infer and generalize from the study's findings. In particular, other factors, besides interoperability, may have played a relevant role in shaping group interaction and team agency, as described in the "Six Sources of Influence model". As, an example, factors such as individual motivation, social skills, class logistics, or access to tools alternative to those provided in class could have played an important role in overcoming (or not) some challenges due to poor interoperability.

Due to the limitations of the design approach and the presence of factors that we could not manipulate or control, we cannot demonstrate, but only suggest causality among the predictor variable (interoperability) and the other variables describing collaboration and design dynamics [73]. Therefore, broadly generalizing causation from this study's findings would be inappropriate. Nevertheless, the study offers many elements of reflection, which can help course designers aiming to establish favorable conditions supporting effective teamwork dynamics. In particular, reflections are especially needed on how to graciously incorporate team members with widely varied backgrounds in order to create productive, inclusive teams.

Supplementary Materials: The following are available online at https://www.mdpi.com/2227-7102/11/3/124/s1, Table S1: Course evaluation form & Final reflection assignment with team assessment.

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References

1. Marble, S. *Digital Workflows in Architecture: Designing Design—Designing Assembly—Designing Industry*; Birkhauser: Basel, Switzerland, 2012; p. 280.
2. Conroy, K.; Riggio, M.; Knowles, C. Familiarity, use, and perceptions of wood building products: A survey among architects on the United States West Coast. *Bioprod. Bus.* **2018**, *3*, 118–135.
3. Muszynski, L.; Hansen, E.; Fernando, S.; Schwarzmann, G.; Rainer, J. Insights into the Global Cross-Laminated Timber Industry. *Bioprod. Bus.* **2017**, *2*, 77–92.
4. Council, U.S. Leadership in Energy and Environmental Design (LEED) Certification. Available online: http://www.usgbc.org/leed.2008 (accessed on 23 August 2020).
5. Lattke, F.; Hernandez-Maetschl, S. LeanWood—Advancing performance of design teams in timber construction. In Proceedings of the World Conference on Timber Engineering, Vienna, Austria, 22–25 August 2016.
6. Gann, D.; Salter, A. *Interdisciplinary Skills for Built Environment Professionals*; The Ove Arup Foundation: London, UK, 1999.
7. Fouger, X. Perspectives from Industry. Sponsor Commentaries. *J. Eng. Educ.* **2008**, *97*, 241–244.
8. Accreditation Board for Engineering and Technology (ABET). Available online: https://www.abet.org (accessed on 23 August 2020).
9. National Architectural Accreditation Board. Available online: http://www.naab.org (accessed on 23 August 2020).
10. American Council for Construction Education (ACCE). Available online: https://www.acce-hq.org/ (accessed on 23 August 2020).
11. Menges, A.; Schwinn, T.; Krieg, O.D. *Advancing Wood Architecture. A Computational Approach*; Routledge: New York, NY, USA, 2017.
12. Bianconi, F.; Filippucci, M. Digital Wood Design. In *Innovative Techniques of Representation in Architectural Design. Lecture Notes in Civil Engineering*; Springer: Berlin, Germany, 2019.
13. Scholl, H.J.; Klischewski, R. E-government integration and interoperability: Framing the research agenda. *Int. J. Public Adm.* **2007**, *30*, 889–920. [CrossRef]
14. Vasconselos, T.; Sperling, D. From representational to parametric and algorithmic interactions: A panorama of Digital Architectural Design teaching in Latin America. *Int. J. Archit. Comput.* **2017**, *15*, 215–229. [CrossRef]
15. Lynn, G. *Animate Form*; Princeton Architectural Press: New York, NY, USA, 1999; p. 203.
16. Schumacher, P. Parametricism: A New Global Style for Architecture and Urban Design. *Archit. Des.* **2009**, *79*, 14–23. [CrossRef]
17. Aish, R.; Hanna, S. Comparative evaluation of parametric design systems for teaching design computation. *Des. Stud.* **2017**, *52*, 145–172. [CrossRef]
18. Payne, A.O.; Johnson, J.K. Firefly: Interactive Prototypes for Architectural Design. *Archit. Des.* **2013**, *83*, 144–147. [CrossRef]
19. Delanda, M. Deleuze and the Use of Genetic Algorithms. In *Designing for a Digital World (Architectural Design)*; John Wiley & Sons: London, UK, 2002; pp. 117–121.
20. Frazer, J. *An Evolutionary Architecture*; Architectural Association Publishers: London, UK, 1995; pp. 65–69.
21. Rutten, D. Evolutionary Principles Applied to Problem Solving Using Galapagos. In *Advances in Architectural Geometry AAG10*; Springer: Vienna, Austin, 2010.
22. Marra, R.M.; Steege, L.; Tsai, C.L.; Tang, N.E. Beyond "group work": An integrated approach to support collaboration in engineering education. *Int. J. STEM Educ.* **2016**, *3*, 1–5. [CrossRef]
23. Haymaker, J.; Bernal, M.; Marshall, M.T.; Okhoya, V.; Szilasi, A.; Rezaee, R.; Chen, C.; Salveson, A.; Brechtel, J.; Deckinga, L. Design space construction: A framework to support collaborative, parametric decision making. *J. Inf. Technol. Constr.* **2018**, *23*, 157–178.
24. Preidel, C.; Borrmann, A.; Oberenderr, C.; Tretheway, M. Seamless Integration of Common Data Environment Access into BIM Authoring Applications; The BIM integration framework: eWork and eBusiness in Architecture, Engineering and Construction. In Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016), Limassol, Cyprus, 7–9 September 2016.
25. Le Roux, S.; Bannier, F.; Bossanne, E.; Stieglmeier, M. Investigating the interaction of building information modelling and lean construction in the timber industry. In Proceedings of the World Conference on Timber Engineering, Vienna, Austria, 22–25 August 2016.
26. Bianconi, F.; Filippucci, M.; Buffi, A. Automated design and modeling for mass-customized housing. A web-based design space catalog for timber structures. *Autom. Constr.* **2019**, *103*, 13–25. [CrossRef]
27. Koppelhuber, J.; Bauer, B.; Wall, J.; Heck, D. Industrialized timber building systems for an increased market share—A holistic approach targeting construction management and building economics. *Procedia Eng.* **2017**, *171*, 333–340. [CrossRef]

28. Staub-French, S.; Poirier, E.A.; Calderon, F.; Chikhi, I.; Zadeh, P.D.; Huang, S. *Building Information Modeling (BIM) and Design for Manufacturing and Assembly (DfMA) for Mass Timber Construction*; BIM TOPiCS Research Lab University of British Columbia: Vancouver, BC, Canada, 2018.
29. Lang, O.; Wilson, C.; Blackman, C.; Gillespie, R.; Krieg, O.D.; Uddin, S. Development of a Design-Driven Parametric Mass Timber. In Proceedings of the Modular and Offsite Construction (MOC) Summit Proceedings, Banff, AB, Canada, 21–24 May 2019.
30. Menges, A. *Morphospaces of Robotic Fabrication—From Theoretical Morphology to Design Computation and Digital Fabrication in Architecture*; Springer: Vienna, Austria, 2013; pp. 28–47.
31. Zardo, P.; Lima daSilva, J. The interfaces between technologies and the design process in AEC industry. In Proceedings of the 37th eCAADe and 23th SIGraDi Conference, Porto, Portugal, 11–13 September 2019; pp. 369–378.
32. Patterson, K.; Grenny, J.; Maxfield, D.; Macmillan, R.; Switzler, A. *Influencer: The Power to Change Anything*; McGraw-Hill: New York, NY, USA, 2008.
33. Kirschman, J.S.; Greenstein, J.S. The Use of Groupware for Collaboration in Distributed Student Engineering Design Teams. *J. Eng. Educ.* **2002**, *91*, 403–407. [CrossRef]
34. Peng, C. Flexible generic frameworks and multidisciplinary synthesis of built form. *Des. Stud.* **1999**, *20*, 537–551. [CrossRef]
35. Johnson, D.W.; Johnson, R.T. *Cooperative Learning and Social Interdependence Theory*; Tindale, L., Heath, J., Edwards, E.J., Posavac, F.B., Bryant, Y., Suarez-Balcazar, E., Henderson-King, J., Eds.; Theory and Research on Small Groups, Plenum Press: New York, NY, USA, 1998; Volume 4, pp. 9–36.
36. Johnson, D.W.; Johnson, R.T. Instructional goal structure: Cooperative, competitive, or individualistic. *Rev. Educ. Res.* **1974**, *44*, 213–240. [CrossRef]
37. Crawford, J.L.; Haaland, G.A. Predecisional information seeking and subsequent conformity in the social influence process. *J. Personal. Soc. Psychol.* **1972**, *23*, 112. [CrossRef]
38. Johnson, D.W.; Johnson, R.T.; Roseth, C. Cooperative learning in middle schools. Interrelationship of Relationships and Achievement. *Middle Grades Res. J.* **2010**, *5*, 1–18.
39. Riggio, M.; Alhariri, N.; Hansen, E. Paths of innovation and knowledge management in timber construction in North America: A focus on water control design strategies in CLT building enclosures. *Archit. Eng. Des. Manag.* **2019**, *16*, 58–83. [CrossRef]
40. Serçe, F.C.; Swigger, K.; Alpaslan, F.N.; Brazile, R.; Dafoulas, G.; Lopez, V. Online Collaboration: Collaborative behavior Patterns and Factors Affecting Globally Distributed Team Performance. *Comput. Hum. Behav.* **2011**, *27*, 490–503. [CrossRef]
41. Dong, A. The latent semantic approach to studying design team communication. *Des. Stud.* **2005**, *26*, 445–461. [CrossRef]
42. Chiu, M.L. An organizational view of design communication in design collaboration. *Des. Stud.* **2002**, *23*, 187–210. [CrossRef]
43. Valkenburg, R.; Dorst, K. The reflective practice in product design teams. *Des. Stud.* **2000**, *19*, 249–271. [CrossRef]
44. Neghab, A.P.; Etienne, A.; Kleiner, M.; Roucoules, L. Performance evaluation of collaboration in the design process: Using interoperability measurement. *Comput. Ind.* **2015**, *72*, 14–26. [CrossRef]
45. Buri, H.U.; Weinand, Y. The Tectonics of Timber Architecture in the Digital Age. In *Building with Timber Paths into the Future*; Kaufmann, H., Nerdinger, W., Eds.; Prestel Verlag: Munich, Germany, 2011; pp. 56–63.
46. Oxman, R. Informed tectonics in material-based design. *Des. Stud.* **2012**, *33*, 427–455. [CrossRef]
47. Leach, N.; Turnbull, D.; Williams, C.J. *Digital Tectonics*; Wiley: Chichester, UK, 2004.
48. Kolarevic, B.; Klinger, K. *Manufacturing Material Effects: Rethinking Design and Making in Architecture*; Routledge: New York, NY, USA, 2013.
49. Oxman, R. Morphogenesis in the theory and methodology of digital tectonics. *J. Int. Assoc. Shell Spat. Struct.* **2010**, *51*, 195–205.
50. Tucker, R.; Rollo, J. Teaching and learning in collaborative group design projects. *Archit. Eng. Des. Manag.* **2006**, *2*, 19–30. [CrossRef]
51. Rutten, D. Grasshopper: Algorithmic Modeling for Rhino. Available online: https://www.grasshopper3d.com/ (accessed on 15 December 2020).
52. Preisinger, C.; Heimrath, M. Karamba—A Toolkit for Parametric Structural Design. *Struct. Eng. Int.* **2014**, *24*, 217–221. [CrossRef]
53. Johnson, D.W.; Johnson, R.T. Effects of cooperative and individualistic learning experiences on interethnic interaction. *J. Educ. Psychol.* **1981**, *73*, 444. [CrossRef]
54. Webb, N.M.; Cullian, L.K. Group interaction and achievement in small groups: Stability over time. *Am. Educ. Res. J.* **1983**, *20*, 411–423. [CrossRef]
55. Johnson, D.; Johnson, R. *Creative Controversy: Academic Conflict in the Classroom*; Edina, M.N., Ed.; Interaction Book Company: Edina, MN, USA, 2007.
56. Johnson, D.W.; Johnson, R.T. *Cooperation and Competition: Theory and Research*; Interaction Book Company: Edina, MN, USA, 1989; ISBN 0939603101.
57. Evans, R.; Difford, R.; Middleton, R. *Translations from Drawing to Building and Other Essays*; Architectural Association: London, UK, 1997.
58. Mueller, V.; Smith, M. Generative Components and Smartgeometry: Situated Software Development. *Inside Smartgeometry Expand. Archit. Possibilities Comput. Des.* **2013**, 142–153. [CrossRef]
59. Hamid, M.; Tolba, O.; El Antably, A. BIM semantics for digital fabrication: A knowledge-based approach. *Autom. Constr.* **2018**, *91*, 62–82. [CrossRef]

60. Gulay, E.; Lucero, A. Integrated workflows: Generating feedback between digital and physical realms. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, Glasgow Scotland, UK, 5 May 2019; pp. 1–15.
61. Schultz, C.P.; Amor, R.; Lobb, B.; Guesgen, H.W. Qualitative design support for engineering and architecture. *Adv. Eng. Inform.* **2009**, *23*, 68–80. [CrossRef]
62. Brown, N.C.; Jusiega, V.; Mueller, C.T. Implementing data-driven parametric building design with a flexible toolbox. *Autom. Constr.* **2020**, *118*, 103252. [CrossRef]
63. Alalouch, C. A pedagogical approach to integrate parametric thinking in early design studios. *Archnet-IJAR Int. J. Archit. Res.* **2018**, *12*, 162. [CrossRef]
64. Ke, F. Designing and integrating purposeful learning in game play: A systematic review. *Educ. Tech. Res. Dev.* **2016**, *64*, 219–244. [CrossRef]
65. Tran, V.D. Theoretical Perspectives Underlying the Application of Cooperative Learning in Classrooms. *Int. J. High. Educ.* **2013**, *2*, 101–115. [CrossRef]
66. Chan, C.; Sher, W. Exploring AEC education through collaborative learning. *Eng. Constr. Archit. Manag.* **2014**, *21*, 532–550. [CrossRef]
67. Breit, M.; Häubi, F.; Holliger, C.; Kündig, D. ICT-Supported Interdisciplinary Project Environments in AEC-Education for Internationally Composed Teams. In Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montréal, QC, Canada, 14–16 June 2006.
68. Akbar, M. Digital technology shaping teaching practices in higher education. *Front. ICT* **2016**, *3*, 1. [CrossRef]
69. Baanqud, N.; Al-Samarraie, H.; Alzahrani, A.; Alfarraj, O. Engagement in cloud-supported collaborative learning and student knowledge construction: A modeling study. *Int. J. Educ. Technol. High. Educ.* **2020**, *17*, 1–23. [CrossRef]
70. Li, B.; Zhang, M.; Jin, R.; Wanatowski, D.; Piroozfar, P. Incorporating woodwork fabrication into the integrated teaching and learning of civil engineering students. *J. Prof. Issues Eng. Educ. Pract.* **2018**, *144*, 05018007. [CrossRef]
71. Wen, A.S.; Zaid, N.M.; Harun, J. A meta-analysis on students' social collaborative knowledge construction using flipped classroom model. In Proceedings of the 2015 IEEE Conference on e-Learning, e-Management and e-Services (IC3e), Melaka, Malaysia, 24 August 2015; pp. 58–63.
72. Colomo-Magaña, E.; Soto-Varela, R.; Ruiz-Palmero, J.; Gómez-García, M. University students' perception of the usefulness of the flipped classroom methodology. *Educ. Sci.* **2020**, *10*, 275. [CrossRef]
73. Donald, A.; Jacobs, L.C.; Razavieh, A.; Sorensen, C. *Introduction to Research in Education*; Nelson Education, Ltd.: New York, NY, USA, 2010.