Innovative CNC Timber Framing - Technology and Cultural Expression

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The design-build project for the outdoor theater roof structure at the UBC Malcolm Knapp Research Forest at Maple Ridge, British Columbia, explores technical, spatial, and cultural aspects of CNC wood fabrication. References for the project are technological innovation and formal expression of contemporary wood structures. The roof project illustrates how spatial concepts are informed by the logic of fabrication and methods of assembly. A reciprocal relationship between technology, space, and locale suggests that the introduction of new technology coincides with new spatial concepts. Innovative design in this project is defined as work that resonates at the intersection of the fields of technology, material science, manufacturing processes, and techniques of assembly that constitute the expanded context that projects need to engage. It is through collaborative design research on CNC wood fabrication technologies that common design and building practice is put into question, and boundaries are explored and expanded.
1. INTRODUCTION

Reevaluation of the context of design and building and the discourse on depleting natural resources and compromised environments has led to extended research on sustainable design methods, building practices, and materials. Beyond the actual performance of building products and components, research on sustainable building is increasingly focused on the long-term effects of the production, application, and life cycle of building materials on the natural environment, human inhabitation, and quality of life.

The design-build project for the outdoor theater roof structure at the UBC Malcolm Knapp Research Forest at Maple Ridge, British Columbia, explores technical, spatial, and cultural aspects of CNC wood fabrication. References for the project are technological innovation and formal expression of contemporary wood structures. The roof project illustrates how spatial concepts are informed by the logic of fabrication and methods of assembly. A reciprocal relationship between technology, space, and locale suggests that the introduction of new technology coincides with new spatial concepts. While material efficiency and origin are part of this research, the perception of utilizing as little material as possible to achieve “eco-efficiency” [1] can be misleading. When “considering that architecture is about more than the development of products for an (existing) market” [2], it becomes obvious that notions of sustainability that are limited to the isolated evaluation of building components and features fail to engage the context of design and building in a comprehensive way. While the amount and origin of a material are significant factors, the ecology of the fabrication process and the final product must also be considered. Consequently, efficiency needs to be understood in an expanded ecological context where questions of adaptability, affordability, durability, and sustainability have to be reviewed considering the particular conditions for design, fabrication, and construction.

Figure 1: Outdoor Theater Roof Structure - Concept rendering
Initial concept renderings for the roof structure as illustrated in Figure 1 introduce the parameters for the research project: the roof is rendered as a lightweight structure using small wood members assembled in a non-hierarchical space-truss configuration. Existing columns serve as a support for the roof structure. The stage, columns, and stepped outdoor seating area have been designed and built as part of a previous phase of the theater project. While covering the outdoor theater stage, the openness and visual transparency of the design responds to the characteristics of the sloped theater site with views of Loon Lake beyond.

2. TECHNOLOGY AND CONTEXT

Technological developments in pre-fabrication, mass-customization, and computer-aided modeling technologies have played a significant role in the transformation of design and building methods towards efficiency and sustainability, as well as the visualization and perception of cultural conditions and developments. Globally available technologies connect the design and building process to a broad range of long-term ecological factors creating a correlation between “the emergent political, economical and social processes and ... architectural techniques, geometries and organization.” [3] Through this interrelationship to economy and culture, technology and its applications are directly connected to notions of place, territory, and fundamental ideas of ecology.

The situation of context-specific design at the intersection of local and global influences has been a common theme since the early 20th century, when industrialization and the increase of mass-produced building materials promoted a sense of regionalism as a reconciliation of the “universal and the regional, the mechanical and the human, the cosmopolitan and the indigenous.” [4] However, applications of technology that were influenced by concepts of modernity have often been treated as independent of space and place. Contrary to these assumptions, the wood design and research on fabrication technology for the theater roof structure highlights the interdependencies of technology, fabrication, context, and place. The design’s relationship to the immediate context is not only strengthened by architecture’s general ability to mediate between landscape and human activity; given the reliance on available technology and material resources, the project’s physical characteristics particular to digital wood fabrication and mass-customization relate it to the circumstances of its geographic, economic, and cultural context. The proposed roof design - Figure 2 shows the underside of the roof structure as seen from behind the theater stage - refers to the orientation of the outdoor theater stage and campground location. As shown in Figure 3, the space-truss configuration of the roof with structural heights reflecting the moment forces within the roof structure orients the activities and the views from the stage towards the
audience. The leaf pattern of the perforated horizontal plywood diaphragm references the forested context.

3. CRAFT AND MATERIALITY

The use of digital fabrication technologies results in a building process that is distinct from traditional timber-framing techniques that are primarily centered on elaborate joinery details. Today, “these techniques are typically considered too labor-intensive and too weak for modern construction.” [5] The shift towards digital design and fabrication processes coincides with the changing use and character of wood building materials. While timbers formed by natural growth retain a place in today’s building industry, monolithic sawn wood stocks are increasingly replaced by new wood building materials such as composites and laminated components. With improved performance these products can result in designs and applications...
that change the way wood is conceived. However, the influence of technological developments in fabrication and building reaches beyond mere fabrication processes. They both affect the entire building process from design to construction and the material performance of structures and redefine craftsmanship by consolidating the position of the designer and fabricator. This transformation is enabled by digital control systems paired with automated fabrication and direct manufacturing systems. Digital production now incorporates the entire building process by coupling design generation and fabrication. It also predetermines methods of assembly.

The outdoor theater roof structure with its focus on wood-to-wood connections for a contemporary design explores applications of traditional joinery that meet current structural requirements while highlighting the potential of wood fabrication and wood joinery. The design research project also reveals the focus of wood engineering in recent years, which disregarded wood-to-wood joints and focused primarily on steel connectors.

4. DIGITAL FABRICATION AND SPACE

Putting forward affordable and efficient strategies that support explorations of complex new geometries, digital media and fabrication technologies promote conceptual explorations and form finding. As systems that readily accommodate custom features, digitally mediated design processes afford designers and builders a new formal and spatial vocabulary. By expanding design possibilities beyond the replication of identical parts, new wood mass-customization technologies challenge conventional notions of economies of scale that assume mass production of unified, standardized building elements. Wood structures are no longer limited to repetitive structures of equal parts and repeated connection details. Moving beyond standardization, new geometries offer formal and spatial flexibility and adaptability; by emulating systems observed in biology and physical sciences, they allow for spatial configurations and expressions that reference complex conditions of the contemporary design context. This capacity for dynamic processes coincides with a paradigmatic shift offered by information technologies.

The development towards complex designs is made possible in part by new tools for parametric design and building information modeling that present substantial new qualities to design practice. Dynamic models offer a degree of flexibility and coordination never previously available. For example, imbedded dependencies and constraints for individual elements allow detailed development of component arrays containing highly specialized individual conditions. While commonly available, timber framing software applications do not support dynamic relationships of components within complex geometries similar to sophisticated digital design programs. However, they associate data specific to the geometry and fabrication of
joints to building components. This joint information can be updated as the form of the structure is revised. In addition, spatially complex digital design models can often be imported into CNC timber framing after the general form finding process. The geometry and fabrication of joints can then be programmed in the timber framing application.

For the outdoor theater roof structure, Dietrich’s CAD/CAM software is used for the joinery design and preparation of data for the Hundegger K2 CNC beam processor. The software, designed for traditional timber framing, provides a wide range of programmable wood-to-wood connections applicable in a 3D virtual environment and translatable into CNC machine language for manufacturing. Each piece of the project is modeled as part of an integrated system thereby allowing visualizing, dimensioning and evaluating every single component of the structure. Parallel to CAD/CAM software, a variety of digital modeling applications are used for the design of the theater roof to explore roof configurations and relationship the roof design to its context. In general, applications such as timber framing software from Dietrich’s and Cadwork Inc. have rendering capabilities that allow illustrating and reviewing wood structures including textures of selected wood types and joint configuration. The applications also help to generate standard drawing sets and component lists. However, for the development and representation of design concepts and their spatial implications as well as detailed representations of projects in their context, typical architectural modeling and rendering applications offer more powerful features.

Simultaneously to digital modeling, plans and sections of the roof are generated with standard drafting applications. While the configuration and detailing of the roof structure can all be developed in 3D models, the plans and sections serve to gain a better understanding of the spatial relationships of the roof design to the site and existing stage during the design process. In addition, the data from sections and elevation of individual trusses within the space-truss roof structure are used to cut truss outlines for scaled models on a 3-axis CNC router. Prior to fabrication, the reviewed designs are then rebuilt using timber framing software to generate accurate representations of the overall roof configuration and the wood-to-wood joints in particular. In preparation for the fabrication of roof elements on the CNC beam processor, the parameters of the joinery details of the roof design introduced in the timber framing software have to match the tool setup of the CNC beam processor used for the fabrication of the roof. The coordination of the tool setup is of particular importance because of variations of the CNC equipment available at the collaborating research institutions and companies.

5. PROJECT OBJECTIVES

The collaborative research and design study for the outdoor theater roof structure at the University of British Columbia Research Forest at Maple
Ridge, B.C., Canada, focuses on the use of digital media in prefabrication and material optimization while exploring contemporary timber framing applications for a spatially complex design specific to its context. Recent developments in digital media and CNC fabrication technologies reverse a trend begun in the 19th century when technological developments led to the decline of timber frame construction by making the production of small and uniform dimension lumber very efficient. The then newly developed construction systems allowed for and extended the use of wood in construction by relying heavily on standardization to improve efficiency of production process. At the same time, the effects of industrialization altered the notion of economy in not accounting for waste and the parallel development of the engineered products industry. However, current timber framing technology promotes the efficient application of wood joinery traditionally used in large section timber to small-scale wood members. These new developments in computer controlled timber framing make structures with wood-to-wood connections economically and environmentally viable as CNC timber framing technology replaces traditionally labor-intensive joining techniques. In addition, introducing wood-to-wood connections as an alternative becomes attractive because of the benefits of building only with wood. Most structural failures in wood buildings due to fire are caused by weakening of connectors. Eliminating metal connectors could result in a more reliable structure while significantly reducing the cost of construction.

6. PROJECT DESCRIPTION

The focus of the project is on innovative uses of timber framing methods and traditional wood-to-wood joints. The challenge of the theater roof project lies in the application of traditional timber framing methods mediated through CNC technology to the proposed roof geometry. While traditional wood-to-wood connections were developed over time using trial and error - precarious connectors were introduced later - the range of established joinery techniques is applicable today using empirical methods for the dimensioning of the elements. The research explores design methods mediated by CNC wood fabrication technology. With this focus, the project explores the potential of CNC beam processing to use small spare lumber from standard larger scale production to generate a complex roof structure, thereby foregrounding the potential of CNC wood processing as a resource efficient building technology.

For the material-efficient lightweight wood structure and its wood-to-wood connections, a Hundegger K2 CNC beam processor is used to fabricate the short 2”x4” wood sections for the 8 x 11 meter space-truss theater roof structure that will be hung from existing columns at the site. A perforated plywood diaphragm provides rotational stability at the top of the roof structure. The bottom plane of the roof is articulated to illustrate the
moment forces within the structure and to provide the spatiality required above the stage. For rain and snow protection, the wood roof structure is covered in lightweight corrugated translucent panels that allow sunlight and shadows of the surrounding trees to animate the space-truss design.

While the design aims to satisfy the specific needs related to program, climate, and locale, the project equally references concepts beyond the site and the immediate context of its intervention by introducing a scale independent of the size and resolution of the wood structure. The roof, with its systems of spatially interlocking trusses, is asymmetrical in order to read like a fragment of a larger continuous surface. While the logic of the wood structure responds equally to the forces in the roof and the orientation of the stage towards the audience, an oversized leaf pattern that perforates the horizontal plywood diaphragm introduces imagery that points beyond the particular scale of the building intervention and camp ground context. Figure 4 shows a plan view of the plywood diaphragm with leaf pattern. The horizontal diaphragm is fabricated using 3/4" plywood. The continuous plywood layer is divided and fabricated in sheets that align with the grid formed by the top chords of the interlocking trusses of the roof structure. The oversize leaf pattern is cut and scored into the plywood sheets using a 3-axis CNC router. Openings are placed where the diaphragm can be perforated without weakening the horizontal stability of the roof structure.

The perforation of the horizontal plywood diaphragm foregrounds the openness of the roof design. Seen from above as described in Figure 5, the leaf-shaped openings integrate the project into its forested setting. Figure 6 illustrates how the sun and shadows project through the perforated plywood layer animate the roof structure and the stage area.
With a focus on resource and material efficiency as well as process effectiveness in wood-to-wood joinery by making use of the smallest members possible, the design research explores the limits of CNC fabrication technology. It relies on the creative use of timber framing software by adapting of traditional standardized wood-to-wood connection provided by the software to the scale of the design and the particular complexity of multiple members connecting in one point. Data prepared for the CNC beam processor in CAD/CAM software results in information defining the complex geometry of each piece. The geometric parameters are then translated by a post-processor to machine language as “G” code that is required for the fabrication of the components.

In parallel explorations, the design is developed with the aid of digital model studies that help to test spatial, structural characteristics, and joinery details, and sample 1:1 joints studies that explore the spatial and structural characteristics of wood-to-wood connections. Figure 7 shows a 1:1 joint sample fabricated on a CNC beam processor. Most effort in the design
process has been put in the reduction of forces that meet at each joint, thereby permitting the use of small section timber for the project.

To minimize forces, the collaborating structural engineers use structural models (see figures 8 and 9) for the calculation of complex load conditions and necessary load transfer in the joints. The analysis of the roof design is completed with 3D finite element analysis programs. These programs use matrix resolution methods to determine exact stresses and deformations in the roof structure. The calculations allow optimizing member dimensions and support conditions to minimize the loads in the joints. The efforts in to reduce the forces that meet at each joint is central to the research because reduced load transfers permit the use of small section timber for the project.
In addition to digital modeling, physical wood models at scale 1" = 1'-0" and 1/2" = 1'-0" are used in the design process to analyze and represent the overall configuration of the roof structure. While joints and structural properties of the roof can only be approximated in the scaled models, the model studies provide basic insight in possible configurations of wood components and joints and also allow the review of principle aspects of the structural performance of the roof design.

It is not conceivable to think of a solution like the design of the Loon Lake roof without digital fabrication technology, given the formal and structural complexity of the project. All building components and cuts are customized to create a spatially and structurally coherent model. The data necessary to formally describe and cut each component of the roof structure, even in a small project, would constitute an unsustainable challenge without the software. The timber framing software allows for the modeling and programming of all building components simultaneously. The review of joints and the overall design in CAD/CAM software prior to fabrication is essential for the reconsideration of wood-to-wood connections as an economical and efficient way of building. While computer generated models, drawings and associated data of timber framing software help to visualize the spatial characteristics of the design and allow for a seamless flow between the design and fabrication phases of the project, structural calculations throughout the design process are particularly important since timber frame structures depend on their connections for structural integrity. Consequently, the design and detailing of joinery is the most difficult aspect of the design and engineering process. With timber framing joints “relying intrinsically on removing material from one member in order to support another” [6] careful development of the joint configurations is of particular importance. This is especially significant when several wood members have to be jointed as part of a complex space truss design.

To configure each component consistent with the structural model of the space truss design, traditional joinery has to be reinterpreted and
modified. Many different configurations were tested to achieve the smallest possible loads. The fact that wood performs differently depending on the direction of the force makes the design of each joint even more complex. Given that components and joints are weakened by the removal of material to allow for interlocking parts, the arrangement of the trusses had to be frequently reconsidered throughout the design process, in order to achieve a feasible solution for each joint and to preserve the original idea of structural continuity.

7. INNOVATION

Innovative design that embraces technology as a key to future development and geographic identity is ecological design. While modern science often relies on an anthropocentric understanding of the environment, the current shift in terminology from environment to ecology signals a reassessment of the surroundings. An extended definition of ecology can expand the scope of design beyond the environmental performance of materials and types of construction to broad cultural considerations. Consistent with an all-inclusive definition of context, aspects of place now include interrelated natural and man-made conditions, including social, cultural, economic, and technological factors. Innovation in design can be understood as a novel re-reading of an existing context. Such an approach emphasizes interdependencies between new design methods and their particular context in material science, economy, and culture. Using an expanded definition of ecological design, context-specific material expression and built form become significant references for architectural design and production. Modes of production and communication play a central role in design grounded in ecology. Interdisciplinary collaboration in design, building, and research, like the roof structure, which benefits from the collaboration of designers, engineers and wood scientists, engages a cultural environment in flux.

The roof design for the outdoor theater seeks innovative technical and spatial solutions. It reintroduces wood-to-wood connections common to traditional European timber framing techniques. Conceptually, the outdoor theater roof project is equally rooted in its local conditions and is reflective of larger processes. By utilizing small square section timber and minimizing the use of alienating connectors, the research on the wood roof structure illustrates the potential of a design culture that seeks innovation in a broader understanding of ecology rooted in regional culture, environmental conditions, economy and tradition. Traditional labor-intensive manufacturing techniques are redefined, aided by computer-controlled machines. Virtual modeling of complex geometries is translated into simple operations. Previous mass-production processes are now replaced with mass-customization, which has given way to the ability to differentiate each building component without affecting the efficiency of the production.
process. The result is a more sensible and accurate response to the context of the design intervention.

While commonly available, there has been very little use of CNC timber framing techniques in modern designs. While “traditional timber framing is most often used as a post-and-beam structural system, where loads are transferred ... on linear paths through massive timber elements,” [5] the roof structure design explores spatial configurations reminiscent of the complex conditions of the contemporary building environment: the small components of the asymmetrical roof design are integrated in a non-hierarchical space truss structure; the different components of the design refer to differing scales of the immediate physical and extended context of the project. In order to generate innovative design interventions that make a constructive long-term contribution to the preservation, maintenance, and evolution of the environment, design needs to be based on a comprehensive understanding of context and the distinctive qualities of the materials used.

The outdoor theater roof design builds on the British Columbia wood building tradition and the existing forestry industry to promote sustainable wood building designs through material efficiency and efficiency of assembly. With this focus, the design research contributes to the transformation of the British Columbia wood industry from a resource-based to a technologically sophisticated and knowledge-based economy.

Digital fabrication tools such as CNC beam processors, CNC routers, laser cutters, and 3-D printers provide a direct link between computer-aided modeling and physical form. For timber framing, CNC beam processors similar to the Hundegger K2 at University of British Columbia Centre for Advanced Wood Processing shown in Figure 10 and Figure 11 are the most relevant digital fabrication equipments. In general, these devices allow for the direct translation of conceptual models into built form and promote evolution of practical aspects of traditional wood building methods. The innovative approach allows development of culturally responsive designs and buildings that explore the “dynamic polarity between technology and culture, between economy and landscape.” [7] The resulting spatial organizations and formal expressions demonstrate an evolving architecture rooted in complex ecologies.

Figure 10: CNC Beam Processor at the UBC Centre for Advanced Wood Processing
8. COLLABORATION
Central to applications of CNC technology is the collaborative exchange between designers, wood scientist, engineers, and fabricators involved in the project to accommodate the diversity of interests, expertise and concerns of all participating researchers. This approach is consistent with the notion that it is no longer possible to understand construction simply in terms of proper use of material. Recognizing that “the age of mechanical production, of linear processes...is rapidly collapsing around us” [8] we need to equally consider material resources, production, design, and assembly processes in order to achieve effective design solutions. Dissociation of influencing factors leads to ecological deficiencies of design.

9. CONCLUSION
The Loon Lake Outdoor Theater Roof is a product of a multi-disciplinary collaborative research process. The interdisciplinary team [A] of architects, engineers, material scientists, and digital fabricators reflects the diversity of aspects implicated by the research into the potential of digital wood fabrication technologies. While exploring the limits of CNC timber framing technology and material-efficient wood construction, the project is driven by the desire to explore CNC timber framing technology for a contemporary architectural solution for the outdoor theater roof. With a focus on wood-to-wood connections, the research project negotiates assumed building conventions and limiting traditional aesthetics while it benefits from the expertise of the collaborating engineers and wood scientists, as well as the guiding input from developers of the utilized CNC fabrication technology and software.

The outdoor theater roof project is one of a number of digital fabrication projects that focus on the context-specific application of digital wood fabrication and building technologies. Currently, a number of design
research projects benefit from the collaborations with the University of British Columbia Malcolm Knapp Research Forest in Maple Ridge, British Columbia, the Universidad Mayor in Temuco, Chile, and private companies. While the University of British Columbia Research Forest provides opportunities to test and realize design research by integrating projects into an active campground, university funding procedures and commercial interests can also interfere with the research focus of projects and influence their realization. A second design research project at the University of British Columbia Malcolm Knapp Research Forest that is currently in the design phase explores solid-wood-wall construction for the design of a mass-customized cabin. The new cabin is to replace historical cabin structures and will be integrated into an existing building ensemble at the campground. Another research project using a CNC beam processor similar to the equipment used for the outdoor theater roof is focusing on the design of a small roof structure for a farm in central British Columbia. This project will be designed, fabricated, and assembled in the spring and summer of 2007. The design research project will be conducted in collaboration with private companies in British Columbia who will provide materials, access to CNC fabrication technology, and fabrication expertise for the project. A collaborative research project of the architecture programs of the University of British Columbia and the Universidad Mayor in Temuco, Chile, in the spring of 2008 will lead to the design, fabrication, and assembly of a small wood structure in Temuco. Similar to the to the second roof project, the design research in Temuco will also be conducted in collaboration with private companies that will provide lumber and access to CNC fabrication technology for the fabrication of the project. All projects involve graduate student research teams. All projects depend on and explore collaborative design research as a basis for the innovative use of digital fabrication technology to generate design solutions specific to their context.

With the final model for the outdoor theater roof structure not yet finished, many aspects of the design still need to be revised. As a pioneer project without precedent, most of the decisions are based in experts’ opinions and the collaborative input of the participating disciplines. The fundamental contribution of this work lies in its experimental character that includes the constant reevaluation of the basic premises of the projects rooted in engineering, material science, and concept-driven spatial and formal explorations. In particular, the complexity of structural calculations of the overall design, the analysis of load transfer in wood-to-wood joints considering structural properties of wood, and the challenge of assembling a non-hierarchical structure play a major role in the analysis of the design process. All results and experiences that derive from this work will contribute to the understanding of the potential of CNC fabrication technologies to contribute to wood-to-wood connection performance and reliability for small square section timber.
Innovative design in the projects outlined in this essay is defined as work that resonates at the intersection of the fields of technology, material science, manufacturing processes, and techniques of assembly that constitute the expanded context that projects need to engage. It is through collaborative design research on CNC wood fabrication technologies that common design and building practice is put to question and boundaries are explored and expanded.

References

NOTES
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