Next Generation CLT: Mass-Customization of Hybrid Composite Panels

This paper examines theoretical and analytical underpinnings to the parametric design and fabrication of performance-based hybrid CLT assemblages to empower architects and engineers with access to powerful digital design and fabrication tools, like traditional craftsmen with their hand tools, to again prioritize material thinking into their design intentions.

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INTRODUCTION

The mass-customization of performance-based engineered wood building assemblies defines a new state-of-the-art in the design and construction of the built environment. This paper describes a novel design research initiative at Washington State University that proposes high performance hybrid cross-laminated timber (CLT) panels to leverage the existing environmental and economic advantages of *mass-produced* forest products and to position CLT as a preferred *mass-customized* building assembly material in sync with emerging parametric design and digital fabrication methods.

Initiated in an integrated studio course of undergraduate and graduate level students of design (architecture, landscape architecture, interior design), engineering (civil, mechanical, electrical), construction management, bioregional planning, business, and organic agriculture, concepts for high performance CLT panels evolved into multiple funded research and teaching activities. This paper specifically outlines the theoretical and analytical underpinnings of a design research project supported by a United States Department of Agriculture - Forest National Institute of Food and Agriculture Forest Products Research grant (USDA-NIFA FPR – award no. 2013-05984). The core product of the ongoing project will be a digital CLT design, fabrication, and assessment platform to be used by architecture and engineering design professionals.

This paper will explore global and local contexts, challenges, and opportunities for hybrid CLT within design research and practice.

EXISTING MASS-PRODUCTION WITH WOOD

As society addresses grand challenges of human population growth, environmental sustainability, and economic stability, an encouraging awareness of the connectivity between the built and natural environments is maturing. This connectivity has long been evident in the forest products industry. Learning from destructive practices of the past, the current forest products industry is deeply intertwined with forest stewardship, sustainable practices, rural community health, and efficient resource utilization. Significant environmental and human health benefits exist with the use of forest products compared to steel or concrete including reduced energy, carbon, and water footprints. These benefits are gaining awareness in the architecture, engineering, and construction professions as a result of education and product/building certification efforts.

However, the strengths realized on the resource end of the forest product supply chain breaks down somewhat on the market end with construction inefficiencies and waste of highly customized wood buildings. The way most wood buildings are designed and built looks very similar to 50 and perhaps 100 years ago. Predominantly, standardized wood building components (sawn lumber, engineered lumber, plywood or strand board panels, etc.) are mass-produced at primary and secondary processing mills and then shipped for final cutting and assembly (customization) on the construction site. The now familiar argument from Stephen Kieran and James Timberlake in their 2003 book, *Refabricating Architecture*, that the architecture, engineering, construction industries are not keeping pace with the optimization, quality control, and mass-customization processes of other product assembly industries such as automotive, shipbuilding, and aerospace—non-building industries that have leveraged the exponential growth in digital design, analysis, and fabrication technologies—is still valid (Kieran & Timberlake, 2003). The challenge to graduate wood building design and construction from site-customization to prefabricated mass-customization generally remains.

Currently, designers and builders of wood buildings primarily utilize a standardized wood kit-of-parts (2x framing members, 4’x8’ sheets of plywood, etc.). This standardization has evolved over a long period and enables individual actors, from a logger in Western Montana (resource end) to an architect in Seattle (market end), to participate within well-defined capacities. The traditions within professional practice and the construction trades continue to reinforce the mass-production of wood products. Despite the aforementioned waste and inefficiencies, many building typologies will continue to be best served by existing mass-production manufacturing and prescriptive-based design methods and codes. Not all buildings demand high performance assemblies or have access to a design and construction workforce trained in advanced systems. Existing pre-fabricated wood panel technologies such as basic CLT and structural insulated panels (SIPs) will continue to serve market demand where high-performance or high-customization at the level proposed in this research is not necessary. However, efforts to advance timber design, manufacturing, and construction to address issues of urban density (taller timber buildings), seismicity (more ductile timber buildings), and sustainability (energy efficiency and carbon sequestration), for example, will demand more rigorous performance-based control and customization.

EMERGING MASS-CUSTOMIZATION WITH WOOD

One could reasonably argue that 10 years after the release of *Refabricating Architecture*, the mass-customization outlook for wood buildings is improving. A dramatic transformation in exposure and training to advanced digital modeling, analysis, and fabrication technologies has taken place in practice and at the academy in disciplines of design, engineering, and construction management. Numerous heavy timber projects demonstrate these advanced expertise and technologies. Yet, these case studies are often unique, high-performance timber scenarios that are not representative of the broader status quo of wood construction and a forest product supply chain at a mature techno-economic equilibrium. This equilibrium and its inherent inertia are difficult to disrupt.

Prefabrication and modular design attempts over the last few decades to challenge current building supply chains, workforce skill sets, and building codes (for example with prefabricated wall, roof, and floor assemblies) often fall short when too narrowly defined within the realm of any one actor or on any particular metric (economics, efficiency, sustainability, quality control, cost, etc.).

Recent market diffusion of parametric design and digital fabrication methods could offer new opportunities to address the plurality in the entire wood resource, manufacturing, design, and construction system. To leverage these technologies, responsive building components and assemblies are needed. CLT is emerging as a preferred building product compatible with parametric design and digital fabrication. With increasing general awareness, infrastructure development, technical knowledge generation, code and standards development, and jurisdiction acceptance, CLT is making a deep and timely commitment into realms of mass-customization and prefabrication.

Originally developed in Europe, CLT systems are gaining in North American markets. Significant research and development has occurred in Canada to adopt CLT technologies into North American wood resources, codes, infrastructure, and environmental structures. Particular technical focus has been given to issues of energy, fire, acoustics, and seismic forces for applicability in Canadian and U.S. codes. Following Canada's North American lead, U.S. federal and state research funding agencies (including the sponsor of this research project, the USDA) are now prioritizing CLT efforts in American markets.

Until codes and standards develop and are adopted, CLT will be necessarily be performance-based and proprietary in North America. Even in mature markets in Europe, CLT panel designs remain primarily proprietary as the ability to control the quality and customize the properties of the product become competitive drivers across many building enforcement jurisdictions.

Innovation within the design of CLT panel assemblies has progressed beyond 'radical innovation' and is a phase of 'incremental innovation' of both product and process. Its dominant product design and form factor is defined (Taylor, 2010). Interestingly, its ill-defined state—one lacking full standardization in design and construction—could be beneficial as the CLT pipeline is developing concurrently with parametric design and digital fabrication market adoption.

CLT DESIGN METHODS

In addition to the inherent aesthetic and material qualities of wood, CLT processes of prefabrication, modular construction, and digital fabrication are attractive to designers and engineers. While market-side AECO partners have access to 'design with' proprietary CLT panels, opportunities to participate in the fully integrated 'design of' CLT panels is limited. The CLT product in its current evolution does not fully embrace the exponential growth and technological advances in parametric design, analysis, simulation, and collaboration expertise prevalent in practice and the academy. AECO partners now demand the ability to specify and tune the structural, acoustic, thermal, and aesthetic performance characteristics of building components and assemblies and to have a direct connection to the material and manufacturing processes. Integrated project delivery models and technology will help bridge the gap between design and manufacturing if building products exhibit the ability for multi-scale customization. Customization parameters might include material composition, form factors, and even sourcing methods. While existing CLT enables some of this customization, hybrid approaches to CLT could extend this customization to additional scales.

Along with the obvious challenge of creating relevant and robust algorithms and models containing these multi-scale parameters, a new challenge for AECO teams is in the design of building components, assemblies, and supply chains that are responsive to these complexities. Considerations of mass-production, customization, and standardization at these multiple design scales will be examined in the remainder of this paper.

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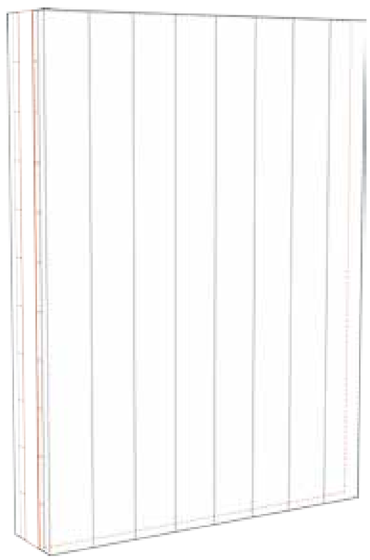


"The understanding of materials as active, whether compressed, under tension, or flexed while handled, is at the root of all craft traditions. The ability to work a material, to saw and chisel wood, to weld and hammer steel, or to weave and knit yarn relies on a profound understanding of its performance."

(Ramsgard Thomsen, Mette; Tamke, Martin; 2013).

Figure 1: Hybrid CLT with solid composite core.

COMPONENT SCALE DESIGN

Material design is controlled at the component scale. While most components of the proposed hybrid CLT panels are mass-produced (sawn lumber for the outer plies, structural connections, etc.), this research examines opportunities for the innovation of a new hybrid CLT, an "hCLT" panel, that replaces the interior plies of CLT with parametrically designed and digitally fabricated (mass-customized) structural composite lumber (SCL) cores (refer Figures 1 & 2).

The concept of a 'programmable' inner core is a significant leap for CLT into areas of biomimicry, resilient design, and emergent design—topics firmly planted in current academic and professional practice architecture and engineering discourse (Oxman & Oxman, 2010, p.15-23).

Digital fabrication (both subtractive and additive methods) at the scale of components are already pervasive in the manufacturing of industrial products, including engineered forest products. In addition, the technologies and parametric modeling methods traditionally used by industrial designers and engineers are increasingly utilized by building architects and engineers. This overlap is transformative as it creates new roles for the building scale designers (architects, structural engineers, etc.) and enables new collaboration pathways with the building component scale (industrial designers, mechanical engineers, etc.). The term 'digital crafting' captures this expanded role of material design to the architects and engineers of buildings and building assemblies—a role analogous to that of master craftsmen.

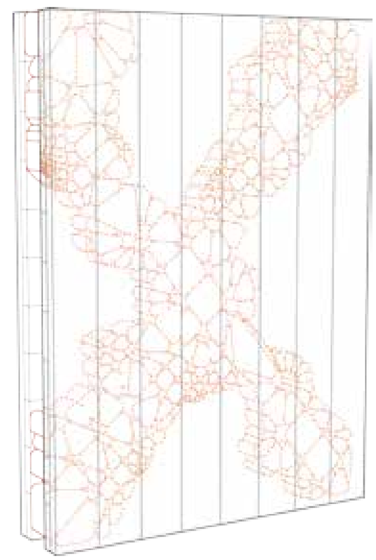
Engineered wood provides a unique opportunity for design at material scales. Wood is an anisotropic material. Its long cellular structure leads to different performance properties parallel and perpendicular to the grain. Additional factors such as species, duration of load, moisture content, irregularities such as knots and checks, etc. all contribute to complex design algorithms. Craftsmen, architects, and engineers have mastered the use of basic sawn lumber over centuries of application. Well understood connections, cuts, and assemblies have evolved within the limitations of its properties. Now, these properties will be scripted into both subtractive and additive digital fabrication opportunities.

ASSEMBLY SCALE DESIGN

At an assembly-scale, CLT attempts to negate the anisotropic properties of the raw material, sawn wood, by alternating the orientation of CLT layers (plies), thus increasing stability in the product. Furthermore, CLT limits the impacts of irregularities by using many pieces of small sawn lumber (often 2x or thinner) to reduce the risk that any one flaw could cause undesirable performance or failure. Parametric factors in a traditional CLT assembly model could include number of plies, orientation of plies, thickness of plies, and species and grade of plies. Numerous non-wood layers and coatings could be added to the exterior of the core wood CLT product to affect performance areas such as fire, acoustics, vibration, aesthetics, etc. Because CLT is generally designed as a solid panel, most current strategies for incorporating mechanical, electrical, and plumbing (MEP) include construction site application of the systems on the exterior of the panels or embedded in the panel after factory surface routing and machining. CLT panel assemblies with various exterior layers and systems integration have received great attention by designers, researchers, and manufacturers and are out of the scope of this paper. Rather, the proposal of a high-performance interior core creates a medium for advanced systems integration (structural, fire, hygrothermal, acoustic, mechanical, electrical, plumbing, etc.) and plug-and-play installation, all informed by the united parametric model.

BUILDING SCALE DESIGN

A hybrid CLT assembly with a parametrically designed and mass-customized wood composite inner core would enable building architects and engineers to "tune" CLT panels to meet performance requirements dictated by custom building designs (top-down) and enable material and system properties and requirements to dynamically inform the macro design of the building (bottom-up). While the outer plies of the CLT panels will hold sectional and material regularity for conformity and compatibility with current CLT standardization and code adoption (in particular fire performance and handling), the material and sectional properties of composite inner core will be designed using algorithms utilizing deep mathematical relationships between component, assembly, and building scale factors.



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An outcome at the building scale is an algorithmic mathematical and geometrical model—a 'genotype' for an infinite number of mass-customized, hCLT 'phenotypes' (Hensel et al., 2010, p.52). In this analogy, the genotype of a hCLT assembly represents the digital model with unchanging genetic information—the parameters, hierarchies, and associations between performance requirements of the panels (structural, hygrothermal, acoustic, aesthetic, etc.). A phenotype of a hCLT assembly represents the unique, mass-customized digital design and physical panel that results from the load inputs and performance requirements from the panel's specific environment. Similar concepts are fundamental to software platforms of building information modeling (BIM) dominate in current AECO professional practice. In BIM, the broad genotype models are called 'families' and are expressed as specific phenotype "instances."

"New design software enables the writing of scripts and codes, that when coupled to simulations of dynamic structural and environmental loads have the potential to extend design processes from the development and fabrication of a singular static artifact or building to families of variant forms that can respond to varying conditions."

(Hensel et al., 2010, p. 11)

SUPPLY CHAIN-SCALE DESIGN

Mass-customized wood panel assemblies have to be assessed within macro-scale contexts of upstream resource networks and downstream consumption networks. Embedding appropriate parametric factors from both environmental and techno-economic models into the product and building models (CAD, BIM) enables optimization, actuation, and education at the AECO level.

As AECO industries increasingly emphasize sustainability through codification and certification requirements, expertise and literacy about products' environmental footprints are maturing. Standardized building product eco-labels that document

Figure 2: Hybrid CLT with conceptual mass-customized composite core.

the environmental impacts of material sourcing, manufacturing, and operation practices are emerging such as “Declare” and the “Cradle to Cradle Certified” (CM) Program (incorporated into the Leadership in Energy and Environmental Design, or ‘LEED’, Version 4 rating system in 2013). Additionally, performance-based codes and certification are emerging that will require advanced digital modeling and analysis and physical measurement and verification of buildings. Energy and carbon are key environmental metrics in these exercises—quantified as either embodied (expended during the making of the building) or operating (expended over the life of the building). Incorporating these considerations into the design of buildings requires an understanding over the entire life cycle of the building assemblies.

Metrics to assess potential impact of technical advancements on these networks are grounded in techno-economic concepts that utilize parametric relationships. Like a parametric building model, the macro-level techno-economic trajectory has a collectively shared logic (Perez, 2010) that factors resource availability, processing capabilities, design and construction methods, code integration, and market acceptance. Figure 3 shows an example network analysis for woody biomass extraction for an allied biofuels project at WSU. Sawn lumber and hybrid CLT serve as a valuable first and best use co-product early in the supply chain. Innovation and parameterization of the supply chain pathways for CLT directly inform the building model and assembly design.

DESIGN RESEARCH TRAJECTORIES

As a product technology, the growth potential for ‘incremental innovations’ in CLT assemblies is still open. The technology of CLT has not matured so far that its innovation trajectory has constricted to resist these incremental innovations that offer significant impacts. This constriction is evident in other mass-produced

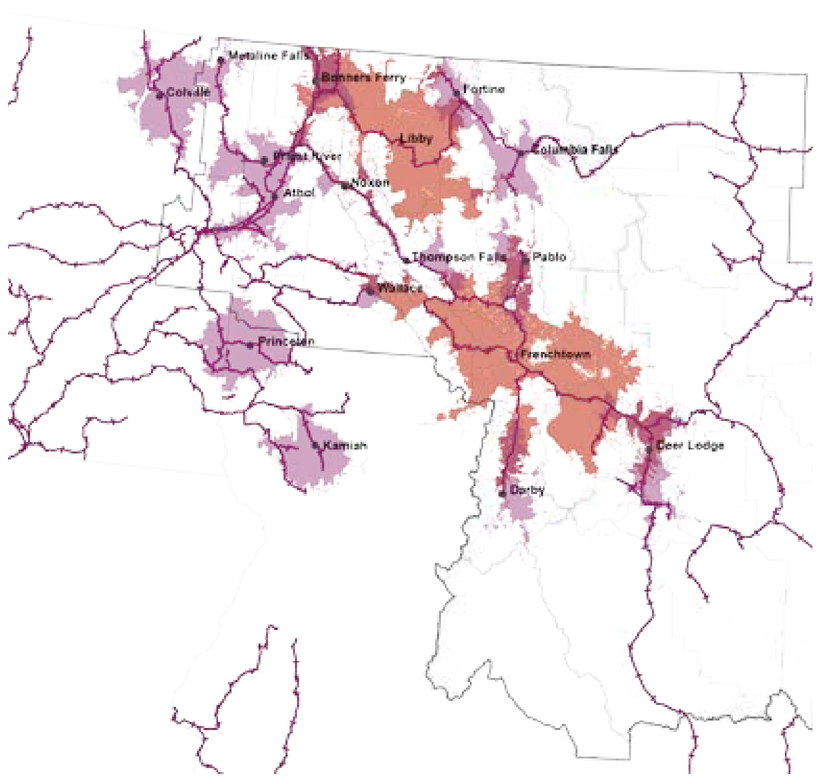

Figure 3: Western Montana Corridor, network analysis of potential woody biomass extraction for establishing techno-economic and LCA parameters. Purple areas indicate 1-hour direct haul to primary processing sites (mills), orange represents 2-hour direct haul to urban secondary processing sites with potential CLT manufacturing capacity (Northwest Advanced Renewables Alliance, 2013, analysis credits Jon Potter, WSU).

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technologies that have found a successful convergence of resource, manufacturing, design, and construction factors. Incremental innovations (let alone radical innovations) to a 4'x8' sheet of plywood or oriented strand board are unlikely to transform the paradigm of what it means to design and build with wood sheathing. This is not to say performance based innovations cannot happen. New coatings, material composition, and even the emergence of "3-layer plywood" (CLT with very thin sawn layers) are advancing 4'x8' sheet product technologies. However, these incremental product innovations will not radically modify the trajectory of how the product is used. Standardization, code acceptance, and workforce familiarity is too mature to allow significant process innovation.

CLT, however, is still accelerating in both product and process innovation. Because this acceleration of CLT technology is occurring at a time of significant advancements and awareness of parametric frameworks and digital fabrication, assessing and capturing techno-economic factors at micro-, meso-, and macro-level scales within the parametric modeling of panel assemblies and buildings is ideal and within the capabilities of the next generation architect.

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