Embodied, Embedded, Emergent: New Digital Strategies for Cross Laminated Timber Fabrication and Use

by

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ABSTRACT

This thesis focuses on analyzing Cross Laminated Timber manufacture and use for the purpose of suggesting ways to enrich involved technology through the further application of digital fabrication techniques. Framed within the context of making and craft, product and processes are explored to search for opportunities where reevaluating current production methods may arise. It is also in this context that concepts of embodied/embedded information and emergence are employed to suggest ideas for rethinking CLT, its fabrication and use. Based on research findings, new CLT panel types are prototyped and their required fabrication approaches proposed. The results are applied to a building design for a site in St. John's, Newfoundland and Labrador.

ACKNOWLEDGEMENTS

I dedicate this thesis to Melanie and Declan for all the support given and sacrifices made throughout my studies. I also dedicate this to my parents Gerald and Sandra and brother Geoff who have helped make this thesis possible. I would like to thank my peers who have shared so many experiences and who have helped along the way. Special thanks go to Richard Kroeker and Emanuel Jannasch for their guidance and friendship during my thesis work and throughout my time at school.

CHAPTER 1: INTRODUCTION

With the continual advancement in high tech modes of making, the idea of craft is at a turning point in the evolution of its understanding. Digital means of working are confronting traditional notions of craft with new thought thus affecting the way we consider design and fabrication. This has profound implications for the world of architecture. How can developments in manufacturing technologies combine with evolving ideas of craft to inform new ways of digital fabrication in architecture?

Digital processes change the way we look at building materials and their production. The possibility now exists to make highly specialized unique components fabricated with mass production efficiency. What this allows is the opportunity for higher degrees of skill and thought to be applied by the architect at material and tectonic levels.

Rethinking traditional ideas about craft can aid in developing new methods of fabrication and building. Due to the involvement of the hand since the origins of making, we often associate craft with manual production. However, a broader definition moving beyond such historical associations is more useful for the advancement of making and fabrication processes.

Digital technologies are bridging the designer/maker gap giving rise to a new form of architect; the architect/craftsman. Historically it was the craftsman in the dual role of designer/maker who would apply their skill to an item created. Architecture as we know it has always involved some degree of designer/maker separation. The very role of architecture was to produce designs for others to execute. This is not to say that skill and thought aren't applied at high levels to an architectural design. It is the design itself that is the product of the architect's craft. However, the digital age is bringing the architect closer to the actual physical making of buildings themselves. Digital designs may be transferred almost directly to the tools of production essentially placing those tools in the hands of the architect.

The intent of my thesis is to examine how digital fabrication may be understood and shaped by changing technology and changing ideas of craft. Using emerging technologies found in the Cross Laminated Timber industry, I aim show how an architect's skill and thought make their way into built form and how this in turn may influence the actual processes of production.

How a new building material or process acquires its architectural voice has been a question asked many times before. How does it gain a richer vocabulary and technological expression? How does it gain acceptance? Architects and critics have long been concerned with issues surrounding the use and appropriateness of new materials and processes. Accompanying this were ideas about the concept of craft. What is its role? Where can it be found? How is it affected by technology? Today we are in a new situation. We are no longer limited to the polarized notions of hand craftsmanship or mass (re)production. The possibilities of custom production on an industrial scale turn previous ideas inside out. How can craft now have an affect on technology itself?

Within this thesis I will explore the notion of embodied and embedded information in Cross Laminated Timber manufacturing and construction processes. Further analyzed through the concept of emergence, the work shall provide a platform to examine ideas surrounding production and craft within the context of 21st century digital fabrication.

Thesis Question

How can developments in manufacturing technologies combine with evolving ideas of craft to inform new ways of digital fabrication in architecture?

CHAPTER 2: CONTEXTUALIZING THOUGHT

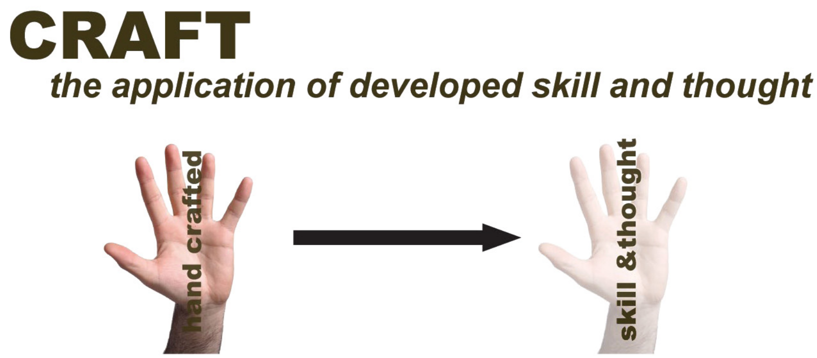
The context of this thesis is situated within and between two primary categories; fabrication and craft. More specifically, key areas of interest in these categories being 'digital fabrication' and the evolving 'concept of craft'. It is in this context that ideas about fabrication and craft shall be analyzed with the aim of furthering an understanding of their past and current states, future potential and their relationship to architecture.

Definitions

Fabrication and craft are each subjects in their own right but the two are greatly intertwined. 'To fabricate' is to make. The term has its root in the Latin fabricatus meaning to fashion, make, build. Fabrication is the act of making; whatever item by whatever means. 'Craft' is a widely used word and has many nuances. The origin of the word can be found in the Old High German chraft meaning strength or skill. 'To craft' is to apply one's skill. Commonly this skill is applied in the act of making. Fabrication may or may not involve skill as it is not at the core of its definition. Crafting however does require some aspect of skill to be applied. Thus fabricating and crafting both describe making but have the possibility to imply different things.

Digital fabrication as the name suggests, is a method of production which uses digital data to direct a manufacturing process (Dunn 2012, 18). Some basic examples of this would be CAD/CAM (which includes a Computer-Aided Design component along with the Computer-Aided Manufacture), CNC (Computer Numerical Control) operations and Rapid Prototyping.

Craft is commonly presented with some notion involving 'the hand'. However, today's emerging production processes, digital fabrication in particular, offer new ways to approach the traditional idea of craft. The current modes of modern high-tech production move the idea away from its historical association with the hand and into a truer essence of craft involving the 'application of developed skill and thought'.



Hand-free definition of craft

Shifting Ideas in Industrial and Post-Industrial Production - How Fabrication and Craft Relate Today

With the rise of the industrial age came ideas about the separation of the craftsman's dual role as designer/maker. Bringing with it a fear for the loss of craft through industrial production, the separation led to strong distinctions between what is 'handmade' and what is 'machine-made'. Goethe's *Art and Handicraft* (1797) is an early commentary of the age and focuses around the concern for the debasing of the arts(craft) as the result of machine manufacture (Frank 2000, 151-152). The writing carries within it a strong divide between artist (designer) and machine; a dualism that still endures today.

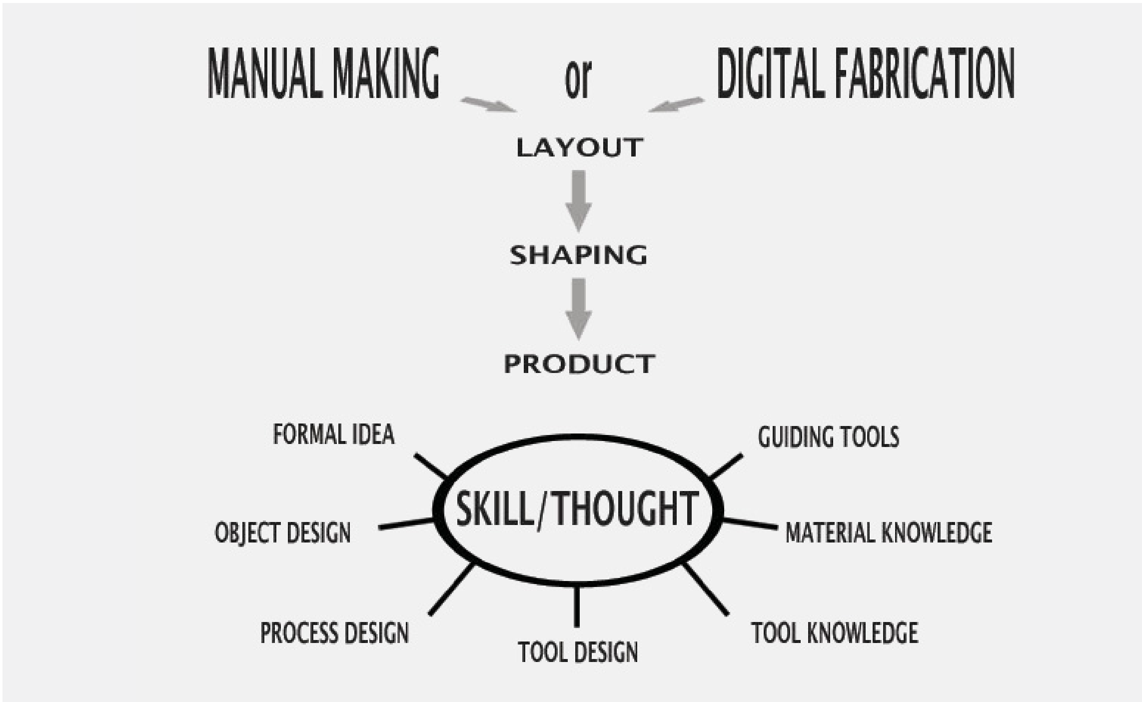
> Did the factory help you grow? Were you the maker or the tool? (MacColl 1990)

A half century following Goethe's work, the continuing discourse is evident in writings such as *The Nature of Gothic* where Ruskin espouses the virtues of the thinking workman and the richness of his work. In Ruskin's writing, machine-like regularity is scorned and industrial laborers are morphed into machines themselves (Ruskin 2005, 14-15). Monica Ponce De Leon states that, "[Ruskin and others] believed that the effect of industrialization had been to change creative practice by separating responsibility for the appearance of a product (design) from the task of fabricating it, with the consequence that the quality of design had deteriorated." While not agreeing with the comment on design quality she continues with, "This is partly true—design as a profession was born out of industrial production's need to separate tasks" (Ponce de Leon 2011) Yes, professionals were producing designs for manufacture through machine processes operated by laborers.

The opposition of designer and laborer is also seen in Hannah Arendt's *The Human Condition* (1958). The work of the laborer, animal laborans, is lightened by instruments invented by homo faber, the tool-maker (Arendt 1998, 144). It is worth noting that Arendt describes homo faber as man working with his own hands as inventor (designer) and maker; essentially in the mode of a craftsman. David Pye also puts the craftsman in the role of tool and process maker. The 'workmanship of risk' (that of a craftsman) is employed to design and build processes and machines for the 'workmanship of certainty' (that of automation) (Pye 1968, 24). The two forms of workmanship are shown to have various roles and interdependencies and at one point it is written that, "Ultimately automation may dispense with the operative altogether; but hardly with the workman, who will presumably remain indispensable to it somewhere" (Pye 1968, 26). This seems to suggest a merging of designer and operator; possibly foreseeing a new form of craftsman.

Today's digital fabrication processes have shaken up two-hundred year old ideas about hand-craftsmanship and mechanized manufacturing. Mass customization over mass production now provides, at an industrial scale, the variety and specialization once possible only by the means of manual making. The use of "computer-aided calculation and production methods, [now] allows for a diversity of individual solutions" (Lehman 2012). Tim Crayton describes various views on mass customization as being "a return to the era of the designer-maker," or "design-to-order" followed by the suggestion that, "one of the key ideas and strategies to achieve mass customization is modularization - products are 'decomposed' into modular components or subsystems that can be recombined to more nearly satisfy consumer needs" (Crayton 2001).

Even more relevant to the idea of 'designer-maker' is how the use of digital design methods and digital fabrication bring a designer closer to the realm of production; closer to the role of craftsman. Digital information provides a more direct translation of information from the designer to the tool; effectively making the information an extension of the tool. Through "[digital] control certain designs can be translated (not interpreted) and 'told' directly to a machine tool so that a prototype or tool can be made" (Pye 1968, 26). The idea of direct commands for custom industrial scale production moves mass customization away from true automatic processes. Automated digital fabrication directed by custom design input is not the same as automatic repetitive production from tuned and statically set tools.



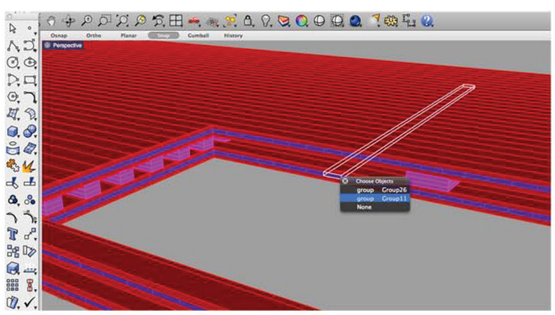
Essential similarities between manual and digital modes of making

We are now in an era of digital design and digital fabrication. With this new situation comes the need for new ways of addressing the designer/maker role. In *The Morphology of Artifact*, Emanuel Jannasch discusses design input as 'information' imparted by a designer or programmer fed more or less directly to machines of physical production. Here the "process of setting up a tool becomes indistinguishable from the process of operating it" (Jannasch 2004, 388). The production of an item is the direct result of the tool being guided by the actions of the designer. In essence, the digital information is produced through the skill of the designer and the imparting of it is the execution of his or her craft. These ideas describe an age of information-rich mass customized products; an age which moves beyond the previous separate notions of low information repetitive mass production and high information custom hand making. We now can see a situation where industrial efficiency combined with precise custom specificity are integrated and lay in the hands of the designer.

Material

A fundamental component of craft is material. It is what a craftsman's developed skill and thought are applied to. Knowing material, how it can and should be used is at the core of craft knowledge. The ability to work material correctly is an essential skill for craft. In his book *The Craftsman*, Richard Sennett describes a craftsman as being continually engaged in dialogue with material (Sennett 2008, 125). A relationship exists making craftsman and material inseparable.

Material is the base for physical making. Expanding on this, 'medium' describes a base for making which includes the physical while also encompassing other forms. This broader view is useful for understanding work within the scope of digital fabrication. In this light, a craftsman operating with digital media does have something to act upon. In *Abstracting Craft - The Practiced Digital Hand*, Malcolm McCullough uses the word medium for showing the parallels in physical and digital craft. He states,"to give work substance, we require a medium," and "the meeting of tool and medium provides a locus for skills" (McCullough 1996, 194-195), showing how medium, physical or not, is tied to craft.



Digital medium

Physical medium

Synopsis

In seeing how craft fits into modern digital processes, a new understanding is being formed. The digital designer/maker is emerging as the digital craftsman. Craft does have a place in modern digital production. What value do these new ideas of craft have for the further development of digital fabrication? How can this be applied to the making of architecture?

CHAPTER 3: CROSS LAMINATED TIMBER - A PLATFORM FOR EXAMINING DIGITAL FABRICATION

Cross Laminated Timber (CLT) is an emerging building material that is steadily gaining notoriety worldwide. Originating in Europe during the 1990's, the product could be described as a massive, plywood-like cousin of glue-lam. Composed of solid lumber organized in layers of alternating orientation, CLT panels are commonly produced in sizes up to 10' x 40' x 12" with a current maximum size of 18' x 98' x 20". Typically the panels are factory cut to sizes and shapes specific to their exact requirements for a particular building assembly.

Image of CLT panel (Binderholz 2013)

Potential size and customized shape of CLT panels

How CLT fits into the digital fabrication discussion is through the technology involved in its production. It is by the use of computer controlled machinery that CLT becomes a viable and practical thing. Because finished CLT panels are shaped to fine tolerances, data driven robotic and CNC equipment is crucial for managing precision cutting at the scale required. To add to this, even before the manufacturing stage begins, the finished and shaped panel is effectively ‘made’ in digital form.

Although digital technology has a strong presence in CLT panel production, there are however some elements which are less digital and more brute industrial. Current CLT practices involve mass production methodology in forming generic panel blanks, or ‘billets’, to serve as base units for subsequent cutting operations. The billet making stage can be seen as a gap in an otherwise continuous high tech process. Does this duality suggest the possibility of reevaluating CLT production? It is within this range of approaches that I am compelled to investigate.

CHAPTER 4: RESEARCH METHOD AND RESEARCH

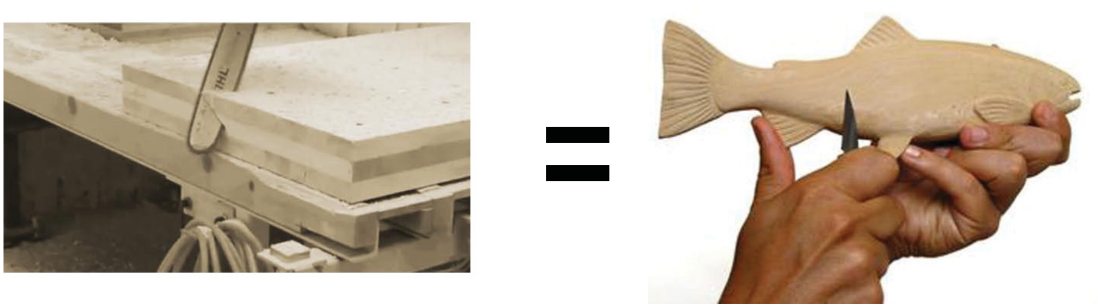
The research for this thesis is to be framed through analysis of Cross Laminated Timber, its production and its use. Elements of CLT technology will be examined as means to understand its position within the realm of digital fabrication. Analysis shall include dialogue on fabrication and craft plus references to relevant examples and precedents of making. Following this phase, the resulting ideas will be explored through design.

Initiating Ideas

Early studies in tool paths and resultant forms left questions about the ‘glue-up and cut-away’ approach of typical CLT production. There seemed to be room for broader applications of current fabrication technology.

Developing technology has often been used for ‘imitative production’ where previously established forms are copied and produced by new means. This phenomenon has long been recognized by architectural and design critics. Hermann Muthesius saw this occurring during the nineteenth century in the production of “surrogate and shabby objects” based on past forms (Muthesius 1994, 13). In the case of CLT production there is however a critical difference.

In CLT processes, new forms are being attempted through techniques which are themselves imitative and antiquated at their core. CNC cutting and milling processes are high-tech subtractive operations akin to their low-tech predecessors of handheld routers, hand planes, drills, chisels and knives. In essence, these processes simply remove unwanted material, however much or little, to leave the desired product remaining.



Subtractive processes of both current CLT manufacturing and hand carving
(base images from Life 123 2013 and YouTube 2013)

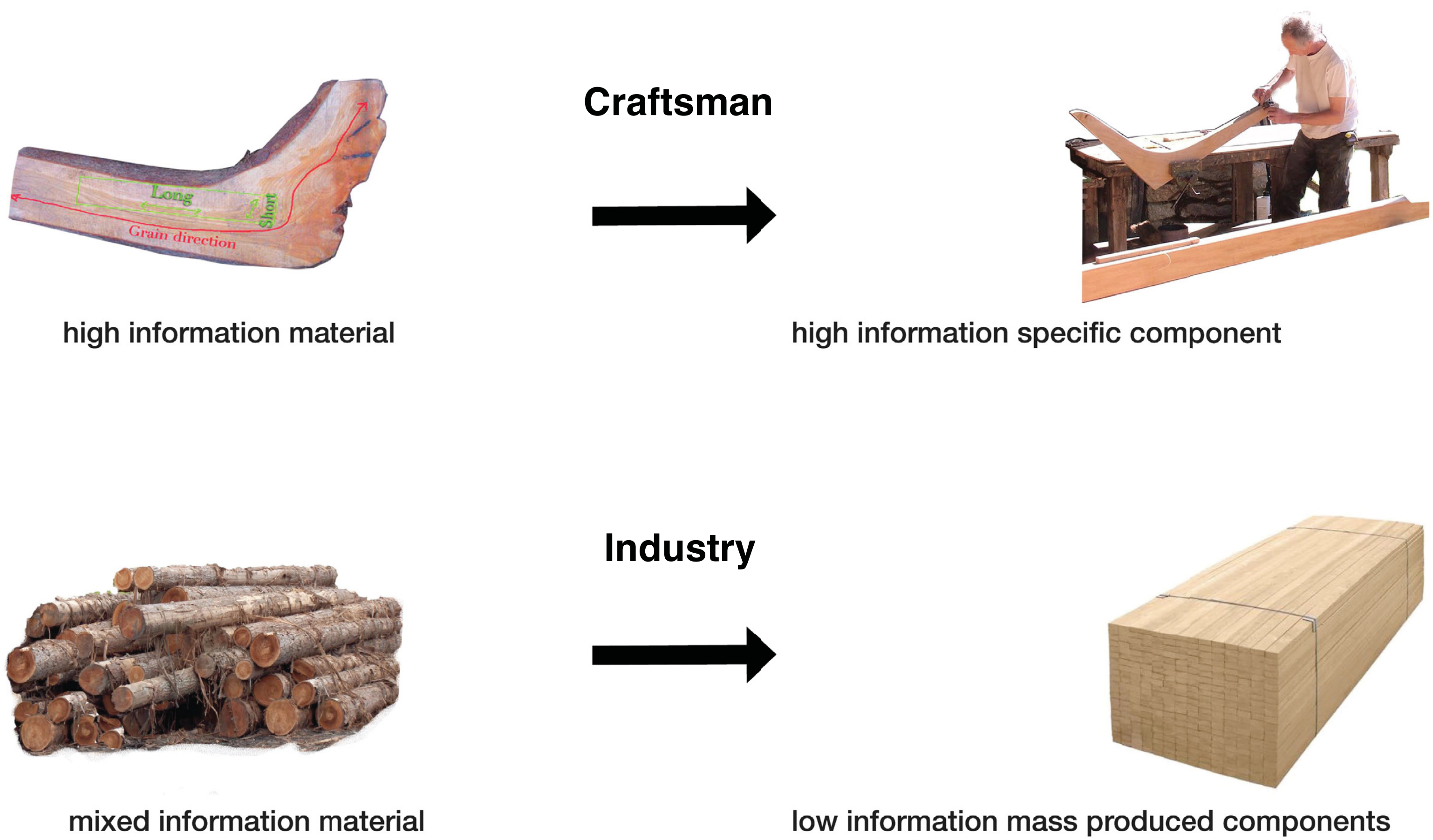
Embodied Information In Material

Before discussing Cross Laminated Timber production in more detail, I will introduce the concept of Embodied Information in material and its relationship to making.

In the act of making, a certain amount and type of input is required to get a certain desired outcome. One key factor which determines the input required is the material involved. How much the material must be worked, and by what means, can affect the choice of material to begin with.

The individual effort of a person engaged in making is quite valuable. Before the advent of industrial modes of working, manual means were the only common option. Considering this, careful material selection could be undertaken to reduce the amount of input effort required. Knowing how to select and use material effectively was part of a craftsman's skill set. Certain qualities which already exist in given materials were sought out and exploited to ease the act of making. For example, the natural curve of a tree branch or root could be used to make a curved item. This ingrained characteristic of a material can be described as its Embodied Information. Such information may exist in high or low levels. In a case where material is fitting or suggestive of a specific final product it is said to exhibit a high level of embodied information.

On the other hand, a common 2 x 4 is considered to have a low level of embodied information. The 2 x 4 has a more universal purpose for more general use. The act of reducing it to its unnatural, rectangular shape requires a great deal of effort while effectively stripping the base material of its embodied information. The ability to do this comes with the introduction of industrial methods of production and the resulting labour economics. The desire to due so has many reasons including maximizing product quantity and standardizing uniformity for compatibility in varied uses. The resulting, almost extruded form, is a result of the basic machine language of straight lines and parallel edges; the simplest and most efficient shape from the technology involved.



Embodied information in crafted and industrial made items
(base images from 1001 Boats 2013, Cast Mountain Log Homes 2013, Coronet 1885 2013 and Lowe's 2013)

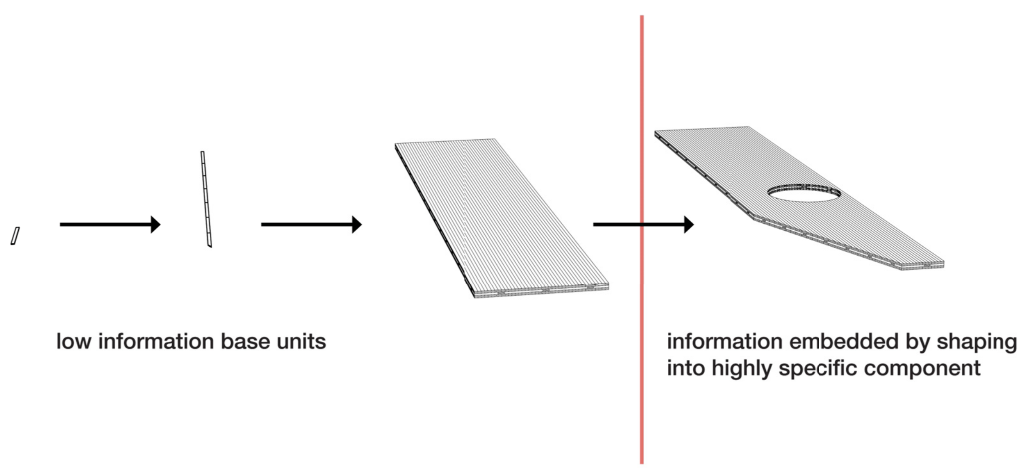
Embodied and Embedded Information In Cross Laminated Timber

CLT is complex in terms of embodied information. It starts out as many, low information universal components but the completed, custom shaped panel is high in information and very specific in purpose. How CLT acquires information is through its production process.

Numerous regular, low information lumber units are complied in the ‘laying-up’ stage. Once arranged, glued and cured, the resulting billet has a new form and new properties. This new state is suggestive of use more specific than those of its constituent parts. It can be said that now the panel has gained some information; information that has been added or ‘embedded’ by the process.

The level of new information at this point however is relatively low in comparison to that of a finished panel. The mass production-like laying-up process yields a fairly generic billet. It is through subsequent digital machining processes that it acquires its specific form and purpose; its complete information load.

The machining stage in the making of a finished panel involves embedding more information into the billet. Digital information from design and fabrication software is applied to the process for guiding the shaping and finishing tools. The digital information now becomes physical in the form of an information rich, highly specific item. The result is a panel which has been designed and produced for one use and one use only; its exact position in a greater building assembly.



Information embedding in current CLT fabrication processes

Such a high information CLT component is fabricated through industrial scale means but unlike mass produced items it is a custom made piece.

In terms of input and yield, CLT does not fall directly into manual or industrial parameters. It involves industrial scale input but the resulting informational content is closer to that of manual craftsmanship. A great deal of input is applied but an even higher ‘effective yield’ is produced. It is thoughtful craft-like making on an industrial level.

Seeing how CLT is made possible by digital technology, the next step involves using such technology to increase the effective informational and performance yield of Cross Laminated Timber.

Can other methods of panel lay-up embed higher levels of information and do so at an earlier stage? Can even more specific properties result from a revised approach to CLT production?

Emergence and Multiplying Properties

Properties exhibited in Cross Laminated Timber are produced by the way in which it is made. As stated earlier, a CLT billet has form and properties different and advanced from its constituent lumber parts. This phenomenon can be seen as ‘emergent’.

Simply put, emergence describes a condition where one plus one is greater than or different than two (Anderson 1972, 395). Emergence is sometimes classified as weak or strong depending on the traceability of cause and effect. Causality is traceable in weak, often simple emergent systems but less traceable or non-traceable in strong. Complex examples of emergence can been found in the dynamic changing shapes of large flocks of birds or in the forming of termite mounds. In any case, emergence is based on the relationship between input and result.

$$1 + 1 > 2$$

$$1 + 1 = 2$$

Simple definition of emergence

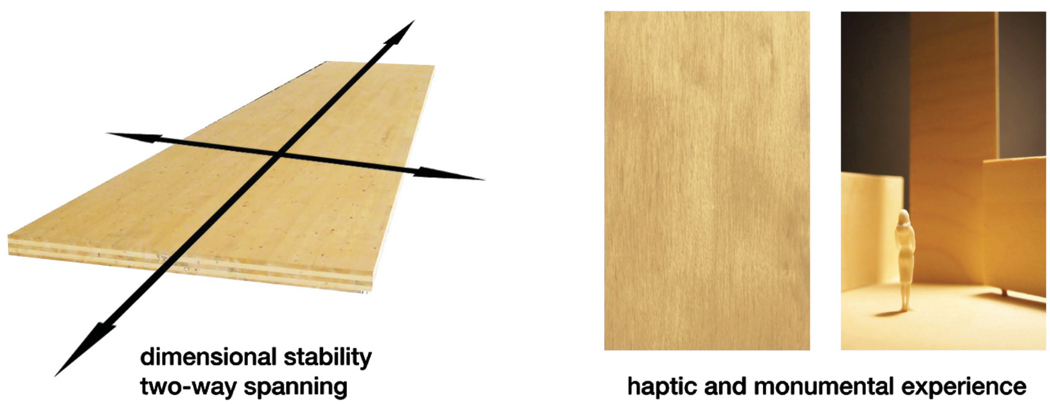
Some forms of emergence, such as swarming, have been applied in architecture with mixed results. These often provide only formal outcomes with no guarantee of architectural resolution (Spuybroek 2008, 211). Unlike such direct formal approaches, emergence shall be used as an analytical tool for the following research.

In its application for analyzing CLT, a more tangible form of emergence will be used; one where results can be both examined and designed with. How can emergence be further applied to CLT to inform new ideas about the material and its potential advancement?

Emergence in CLT

In making a simple CLT panel, the arrangements of the constituent parts create something more than just an equivalent mass of wood. The panel has gained longitudinal and lateral dimensional stability. It can span in two directions when oriented horizontally and act as a beam or compression member when vertical. It can resist shear forces. Also, due to its size, CLT is considered ‘heavy wood’ in fire rating terms. These physical properties come from the alternating orientation of its layers plus its great, monolithic mass; qualities not found remotely equivalent in the constituent lumber units alone.

Experientially, CLT again becomes something more. It is both haptic and monumental. When exposed, distinguishable lumber members can be read on a human scale. Combined with the grain of the wood itself, a tangible and familiar nature is revealed. At the other end of the spectrum, a single panel may reach sizes that would easily dwarf an individual. This multiplicity of scale through ‘many comprising a whole’ can be seen as another example how the total is something different than the simple sum of its parts.



Emergent properties in CLT

A multiplicity of emergent properties along with the complex and dynamic nature of CLT suggest the potential for expanded methods of production and use. Could an alternately designed fabrication process bring forward greater emergent results?

CHAPTER 5: PROPOSING A PROCESS, PROPOSING A PRODUCT: SYSTEM INTEGRATED CLT

Rethinking the laying-up stage of CLT production shows promise for increased emergence. One simple way to alter the process would be to create a billet profile more specific to the finished panel. Instead of first producing a large rectangle for cutting into shape at a later stage, a billet could be assembled directly in its final desired form. The particular shape result introduces another level of emergence.

Such a process would require changes to the equipment involved. Firstly, some type of ‘smart’ technology would be needed to sort and layout the lumber. In addition to this, a more complex press may be required during glue-up. To redesign the lay-up process for only addressing billet profile may not alone warrant the increase in complex technology. However, if employed for higher yield work, such technology could prove beneficial.

Integrating various systems and properties into CLT panels is another approach to raising levels of emergence. More thoughtfully designed lumber arrangements would lead to an increased multiplicity of results; essentially greater emergence. Air ducting, insulation voids, electrical and plumbing chases can be built directly into a panel during its fabrication. Such panel types would be highly specific in design, production and use and therefore extremely information rich. Building systems incorporated directly into CLT could provide a great enough effective yield to make the production requirements viable.

The value in searching for greater emergence comes from the value of increased functions or properties. Combining many features into fewer components aligns with ideas of higher yield through craftsmanship. Multiplicity in emergent outcomes describes a kind of poesis where bringing forth desired results through careful design and integration can significantly reduce the effective input.

Knowing where and how to apply new ideas to CLT production is explored and developed in the following sections.

Further Analyzing Research through the Design of a Process

Integrating systems within building components at the stage of production is not a new concept. Examples of air heated wall brick can be found in ancient roman baths as part of hypocaust systems. Voids within modern hollow core concrete slabs can be used to channel air or serve as electrical or plumbing chases. Currently however there are no explicit examples of CLT components featuring integrated systems.

The various technologies needed to make advanced, system integrated CLT components do exist. Putting those technologies together as a process is what is required. In their book *Refabricating Architecture* (2004), Kieran Timberlake highlight how architecture, when compared to other fields, often lags in implementing modern digital fabrication approaches. Examples of advanced processes from the automotive, shipbuilding and aircraft industries are presented with suggestions of how they could be applied to enhance building technology as well as architecture itself. Information control systems, mass customization and digital modeling are some of the topics explored in their writing. These and other similar tools and processes will be called upon for the following rethinking of CLT production.

Designer/Maker and Scale

Due to the large scale of production for CLT and many other digitally fabricated objects, the ‘designer/maker’ may have to be something larger in scale as well. What this means is that a team of people act as what was previously more individual in nature. By allowing for the idea of a designer/maker team, possibilities arise for members to work in different places geographically. Design and production does not need to take place in the same location. There must however be a continuity of process. This continuity comes through the direct translation of ideas and design between phases; including the point where processes move to production and design data becomes control input for machine operations. What makes the required continuity possible is the use of digital information control.

Mass Customization

Mass customization is a term applied to processes where custom results can be achieved at or near mass production economy. It is a clear departure from the nineteenth century repetitive industrial manufacturing methods still common today. “This situation has been transformed through digital fabrication methods, wherein the multiplicity and complexity of design elements has no correlation to economies or efficiencies of production" (Dunn 2012, 84).

Cross Laminated Timber fabrication is an example of a mass customization process. One of a kind panels, specific to a precisely determined use, can be produced at a rate no different than multiple panels of repeated design. This quality of CLT manufacturing permits any range of customization without diminishing production efficiency.

The Redesigned Process

The first stage in the design/making integrated fabrication process for CLT is design. Although the required format for producing a physical component is a digital model, a combination of digital and physical media may be employed in the initial design stages. Constructions of a building design and its parts may be translated back and forth between digital and physical worlds through digital and analog means. - The term construction is used here as a means to describe an active, working part of a continuous design/making process as opposed to static architectural representation (Spuybroek 2008, 7).

Because in architecture, "the ability to effectively communicate creative ideas remains a central aspect of the discipline,"one should not be [and is not] limited in modes of design (Dunn 2012, 6). Digital scanning and prototyping in conjunction with manual making can provide a more complete development of design. Ultimately, following the use of any combination of media, a digital model is made.

Building Information Modeling

Following whichever design processes chosen, a digital building model is made. When complete, the model will be ready for stages preparing work for fabrication. To successfully manage and integrate systems effectively within the model, certain software such as BIM is required. Building information modeling programs have the needed tools for executing the demands of overlaying and meshing required systems for holistic building design.

Often considered a 5-D modeling tool, BIM not only models the three spacial dimensions but time and cost as well. A single model is capable of being interfaced by multiple designers simultaneously and has the ability to highlight system design clashes. Assembly types can be detailed and applied where needed throughout the overall model. It is these properties of BIM that make it applicable for the complex system organization of integrated CLT building and panel design.

As various systems are incorporated into the building model, integrated panel designs emerge. Profiles and voids are overlaid while structural, fire and other performance requirements are checked and adjusted for. At this point the panels themselves are represented as solids and voids with the actual component assembly protocol to be determined in the next stage.

Determining Lumber Specifics and Generating Parameters

Following the completion of a BIM model for building design, the whole is then broken down into specific component models as the process prepares for fabrication. Component models are further articulated in terms of the necessary lumber configurations needed to form an integrated panel. In ways, this is analogous to modeling for rapid prototyping production. Lumber units effectively become large wooden pixels to be laid out in a highly determined manner.

Industrial design and parametric software may be most effective at this stage. Rhino with a Grasshopper plugin can determine and optimize needed configurations of lumber. With this, an even finer grained model of each individual lumber piece is produced. Dimension and position parameters are produced and encoded as fabrication data by means of computational scripting. An identification code is then assigned for subsequent stages.

Processes similar to this have been developed and employed at Dalhousie University's School of Architecture *Cybertectonics* workshops. Multi-component digital models of designed objects were created and broken down into parts. Geometry data was then generated and encoded for fabrication purposes. The digital information was finally translated for custom built electronic and mechanical actuators to aid in the cutting of physical components.

The next stage of integrated CLT production begins the physical making of a panel.

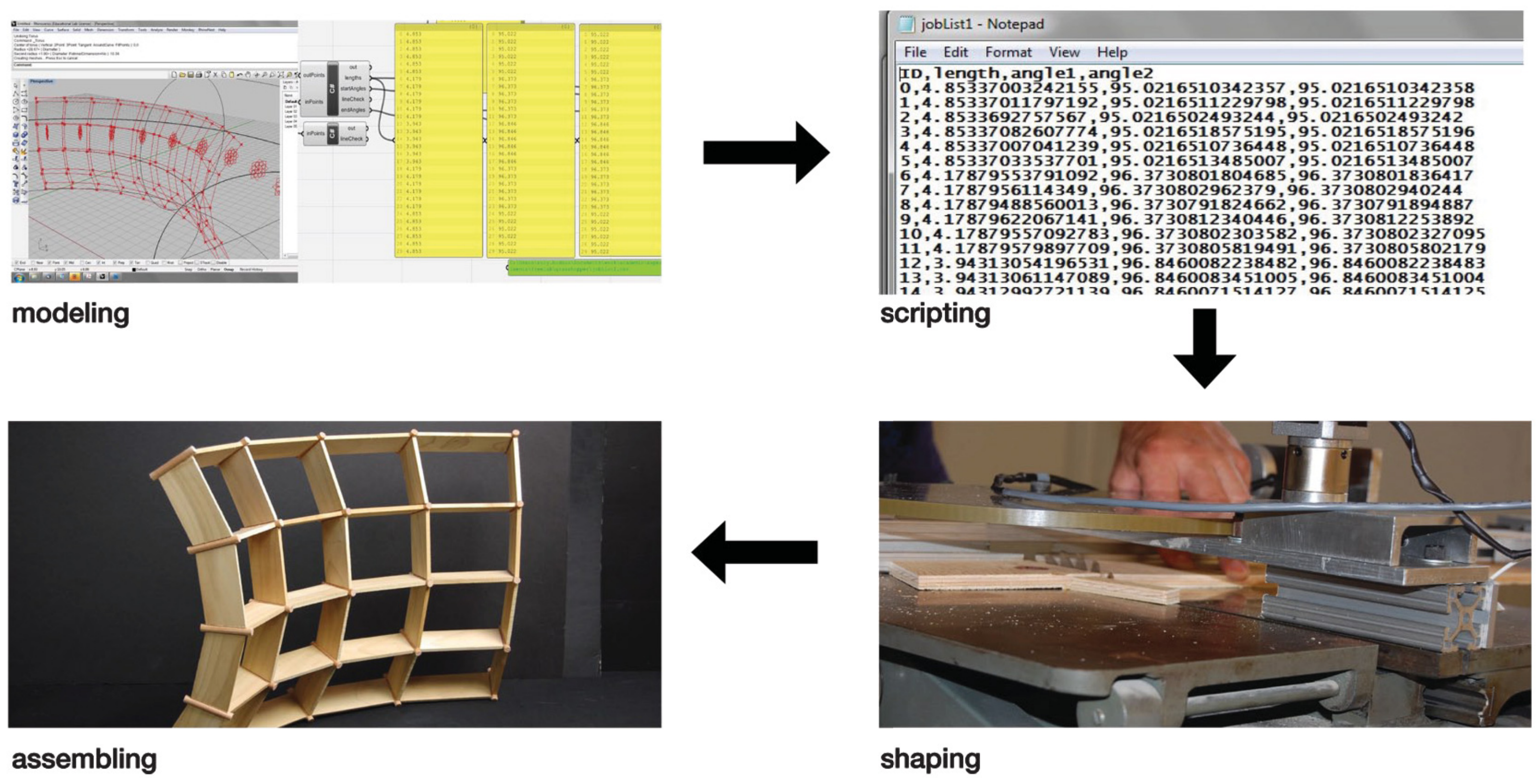


Diagram showing stages of Cybertectonics workshop 2010
(images from Hudson 2013)

Lumber Selection and Tailoring

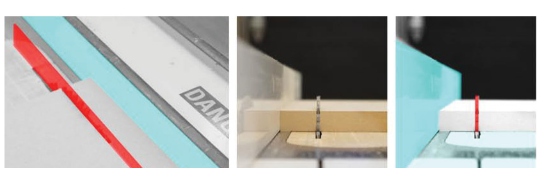
Gathering and refining the basic building blocks for an integrated CLT initiates the physical production processes. Lumber is selected and arranged through robotic sorting technology. Printed codes are employed for identification scanning to locate and position lumber members during this procurement phase and following laying-up stages.

Optimized regular members are retrieved from standard dimensional lumber groups and restocked into a specific panel batch. Running in parallel with this, non-standard members are selected and cut as informed by specific encoded data. These tailored units are brought into the panel batch as well to complete a virtual and physical bill of materials.

Laying-Up Wood Pixels

Once a specific panel batch is collected and tailored, it is time to begin laying-up the members. It is this stage that presents the biggest departure from current CLT manufacturing.

Common CLT production involves assembling lumber members en masse into large solid billets for subsequent shaping. The revised integrated CLT fabrication process requires a more thoughtful approach to panel lay-up which allows variation and features to be built directly into a panel. This demands a change in the 'language' of making. The machine language present in the build-up then cut away method for current CLT production does not provide the dynamic forming possibilities required for system integrated CLT. A digital language of making, closer to what is seen in rapid prototyping, must be applied for the revised fabrication process. By viewing lumber members as pixels, a new manner of forming is described; essentially 'wood printing' of CLT.



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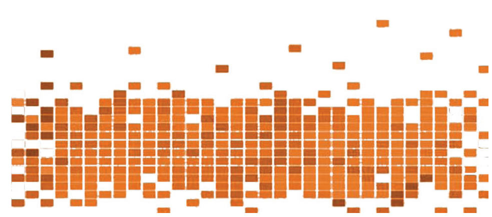


Machine shaping

Digital forming

Wood pixels may be of regular size and shape, similar to the lumber used in common CLT billets, or may be unique, tailored members for specific use. This means that pixels range from small, unique wooden blocks to long, finger jointed boards.

Through the use of sorting and tracking technology, members are retrieved from panel batches then glued and placed according to specific panel design. Robotic technology would be used for this stage due to the vast amount of detailed sorting and placement information.

Swiss architects Gramazio and Kohler make use of similar robotic assembly technology for various built and research projects in brick and wood.

Image of Gramazio and Kohler's wood stacking robot (Fabricating Architecture 2013)

Laying-up of system integrated CLT components may sometimes require a multi-staged approach due to gluing, clamping and support complexities. Whole, multilayered panel 'skins' may be first produced to be built upon with complex internal organizational members. Such subassemblies would be treated as tailored constituent members themselves as part of a multi-stage bill of materials. The use of subassemblies is commonly found in automotive manufacturing. Subassemblies, or chunks, are made up as a part of branched sets of operations. A primary benefit of chunk use is its focus on smaller, more manageable operations. This allows for subassembly production to occur in various locations, near or far, helping to avoid ‘traffic jams’ on the factory floor. Also, through chunk making, higher quality standards arise from both elevated levels of manageable attention to detail and an overall reduction in the number of joins needed (Kieran 2004, 95). Subassembly based production can ultimately speed up manufacturing process while improving quality; a double win.

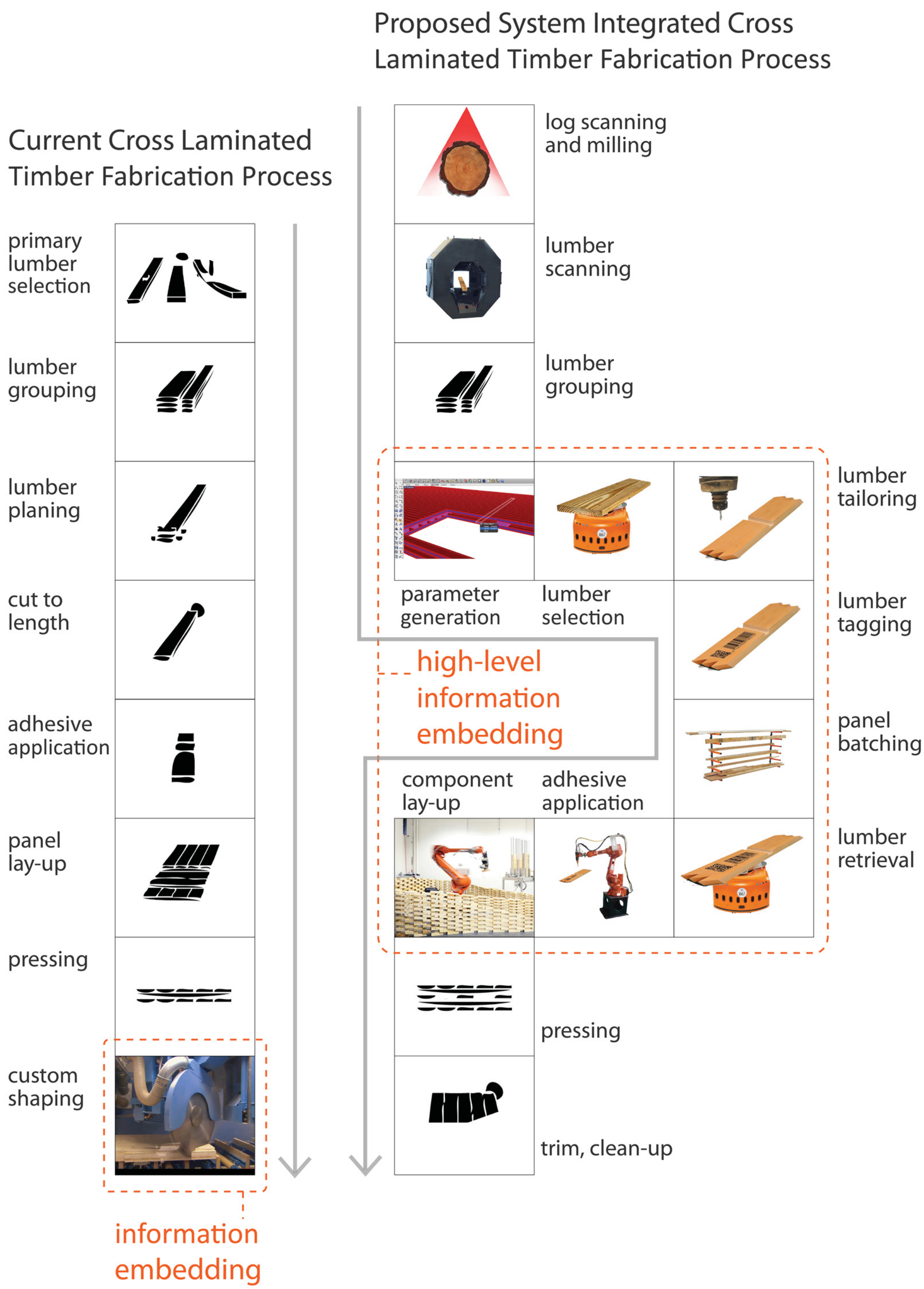
The described method of revised panel lay-up is crucial for achieving multifaceted results desired in an integrated CLT component. Current methods of simply assembling an entire, solid CLT billet with the intent to mill special features leaves only profile and surface details possible. The internal workings of an integrated panel could only be made within the make-up of a panel itself. It would not be feasible or even possible to core out a billet with any degree of complexity after the fact. To attain the high yield of results possible in integrated CLT, the ‘printing’ of wooden pixels is the most appropriate method of fabrication.

This method of thoughtful laying-up is essentially a scaled down but higher tech version of CLT building assembly. Like constituent lumber members, tailored CLT components are designed, produced, sorted and assembled into a greater whole.

By applying ideas of emergence and embodied/embedded information to the overall building scale, more layers of potential ‘results’ can be achieved. Maintaining the continuity of approach through scales allows for a highly integrated building ‘organism‘ featuring a multiplicity of crafted results.

Panel Finishing and Building Assembly

Following lay-up, integrated CLT panels are supported and pressed as needed while glue bonds cure. Clean-up with CNC and robotic processes follow to refine and finish panels. Labeling and sorting then groups panels into an organized, building-scale bill of materials. Packing and shipping preparations are made before sending parts to the construction site. Finally, the CLT design/making process is completed by assembling panels into the building form itself.



Comparison of current and proposed CLT processes highlighting stages of information embedding (thumbnails from Fabricating Architecture 2013, IEEE Spectrum 2013, Made in China 2013, Wood Business 2013, Woodcraft 2013 and YouTube 2013)

CHAPTER 6: DESIGN METHOD AND DESIGN

An alternative approach to the digital fabrication of Cross Laminated Timber has been generated through the preceding analysis of CLT production processes. Examined within the context of fabrication and craft, research has suggested that the concepts of embodied/embedded information and emergence be used to inform ideas for rethinking CLT production. To increase effective yield through heightened information and emergent results, the idea of system integrated CLT has developed.

To begin designing with the research results, prototypes of integrated system panels shall be produced. Through various constructive means, the process of integration will lead to particular approaches in the buildup of the panels themselves.

Digital and physical methods of design and making will be employed for prototyping and subsequent work. This is intended to simulate concepts developed within this thesis because a physical incarnation of the proposed process is beyond my personal means.

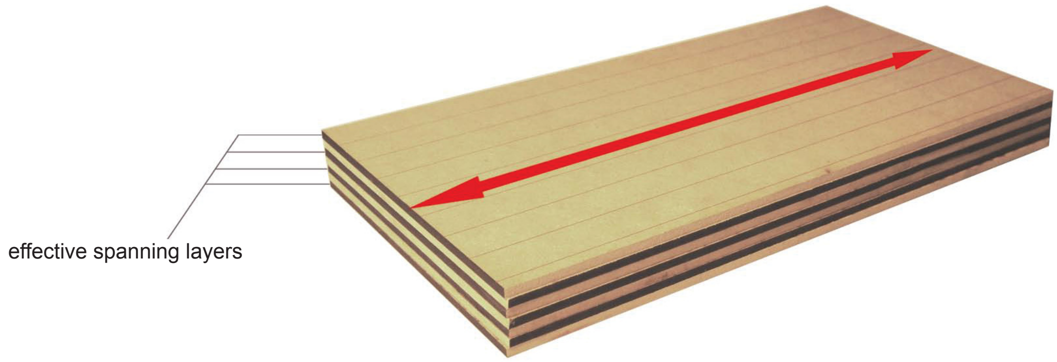
Following panel prototyping work, resultant approaches and considerations will be used at system and building scales to inform design based around digitally fabricated integrated CLT.

Once a building design has been established, several typical panel types shall be further developed showing building-panel relationships.

Panel Prototyping

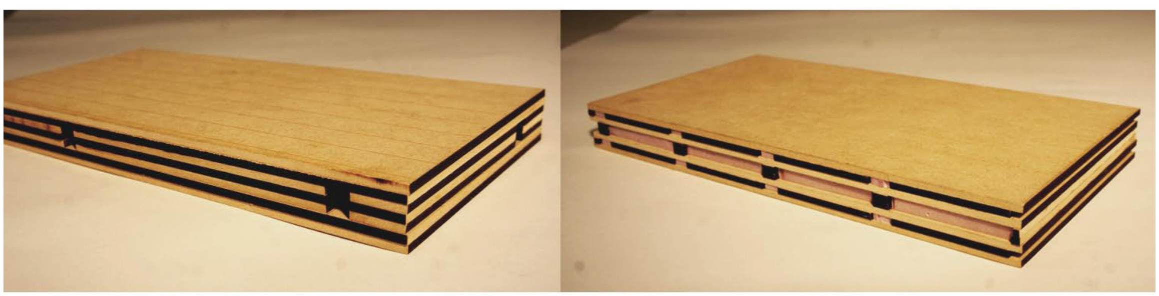
Primary characteristics of Cross Laminated Timber will be respected in the following prototype work. It is the goal of this thesis to work in the mode of CLT and its nature. One major characteristic of CLT is its general ‘panelness’. Overall forms will generally remain as panels but panels which have been ‘teased’ apart. Another key CLT characteristic is its use as structure. This will remain prominent in many panel prototypes.

In recognizing core CLT principles, examining specific physical material qualities led to the first steps in developing prototypes. Upon looking deeper into the geometry and properties of CLT, it became apparent that internal reconfiguration would be highly dependent on working with the effective and non-effective (lesser-effective) layers of the panels themselves.



Model showing the effective layers of a CLT panel with endgrain picked out in dark brown

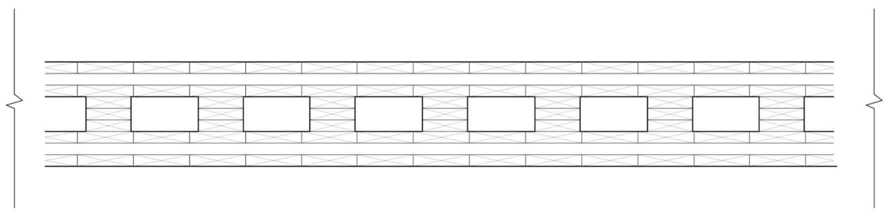
The effective layers of a CLT panel are those whose orientation determine them to be primary players in a given panel type. For example, a floor panel acting as a one-way slab would have the layers oriented across the span as its effective layers. For a load bearing wall, vertically oriented layers would be considered more effective in carrying loads through the length of their wood grain. This is not to say that ‘non-effective’ layers have no role. They do play a part working with the effective layers and also add certain properties in their own right. It is important however to consider the effectiveness of each layer when determining how they are to be arranged for system integration.



Models for experimenting with the manipulation of effective layers

The properties of a given system also affects how it is to mesh with panel orientation and structural requirements. To give an example, a ventilation system is one which requires highly continuous cavities for air flow. When combined with the directional properties of a floor panel, it suggests that air should travel parallel to unbroken members of the effective layer. Spanning members of the effective layer may be rearranged to accommodate air flow providing they maintain any needed structural requirements. The result is a panel featuring internal spanning ribs flanked by air passages.

Effective layer model of proposed CLT panel featuring integrated air ducts

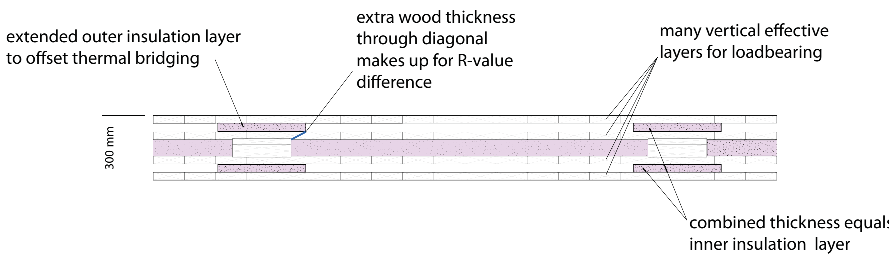


Cross section drawing of proposed CLT panel featuring integrated air ducts

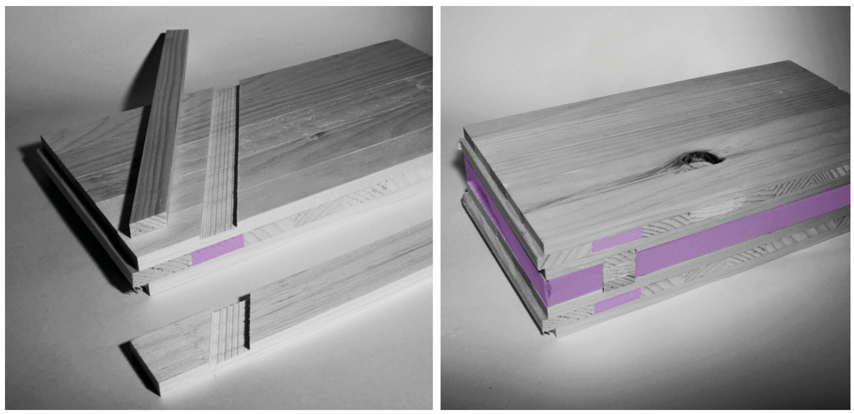
1:1 partial model of proposed CLT panel featuring integrated air ducts

In designing for integrated requirements, knowing how to act upon effective and less effective layers or members brings forth the specific geometries of a panel; essentially embedding information into the piece.

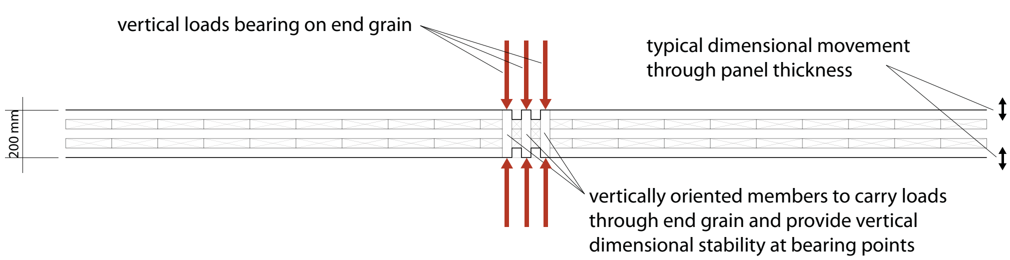
It is this type of specific geometry (information) which is designed and built into each panel during its making. Careful tailoring and arrangement of the constituent wood elements bring forth the multiple combined results within an integrated CLT component.



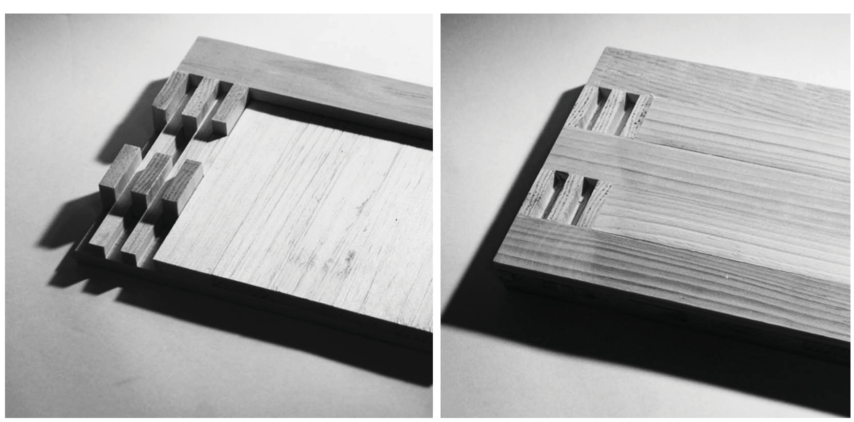
Cross section of an insulation integrated panel highlighting design considerations



1:5 partial model of an insulation integrated prototype during and after assembly



Cross section of a vertical load transfer panel highlighting design considerations



1:5 partial model of a vertical load transfer prototype during and after assembly

By designing specific panels and how they relate within a system, another scale of results emerge. Through the design of a building, each (tailored) panel is laid out as part of a specific arrangement giving rise to system and spacial forms.

Applying Ideas to a Building Design

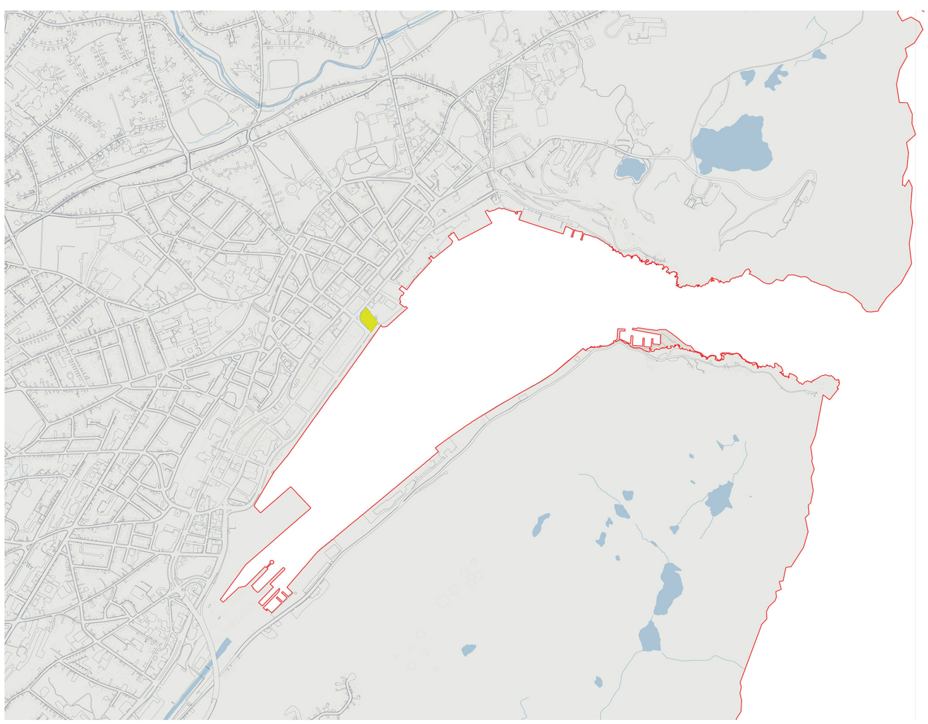
Using accumulated results from the thesis study thus far, a system integrated building design will be developed. Methods and ideas drawn from the design and fabrication of CLT panels shall be employed where applicable for the building concept.

Site

The site chosen for the thesis building design is located in downtown St. John's Newfoundland and Labrador. Currently a mostly cleared lot with only the remains of a one storey brick vaulted basement mass, the site itself is level ground sitting at approximately three meters above sea level. The southeast boundary meets the federal wharf of the harbour while roads to the northwest (Water Street) and southwest (Job's Cove) meet at a prominent intersection.

Aerial view of thesis site from south (base image from Bing 2013a)

Map of the Northeast Avalon Peninsula showing site and harbour location
(base image data from GeoGratis 2012)

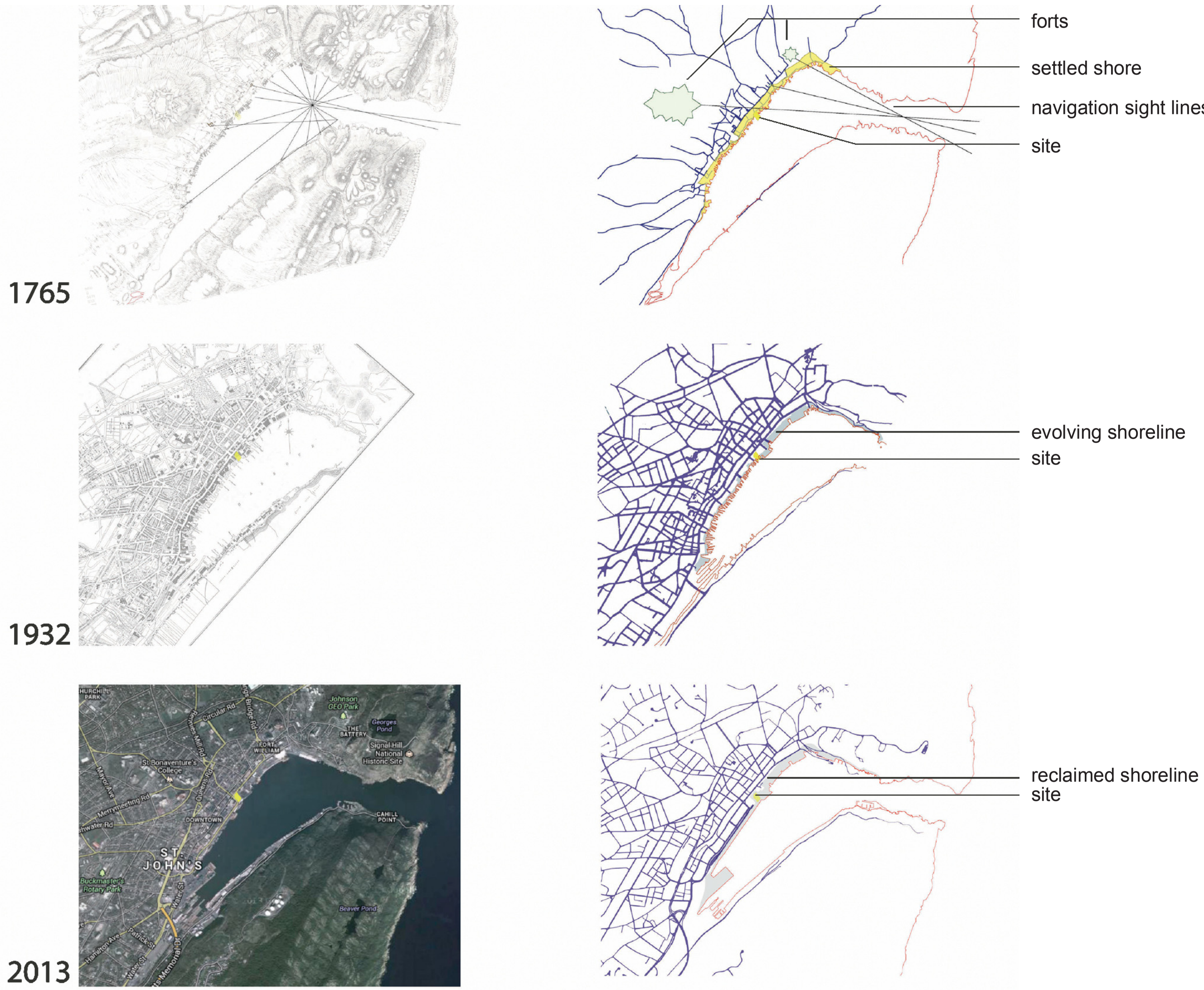


Map of St. John's Harbour with site highlighted in green

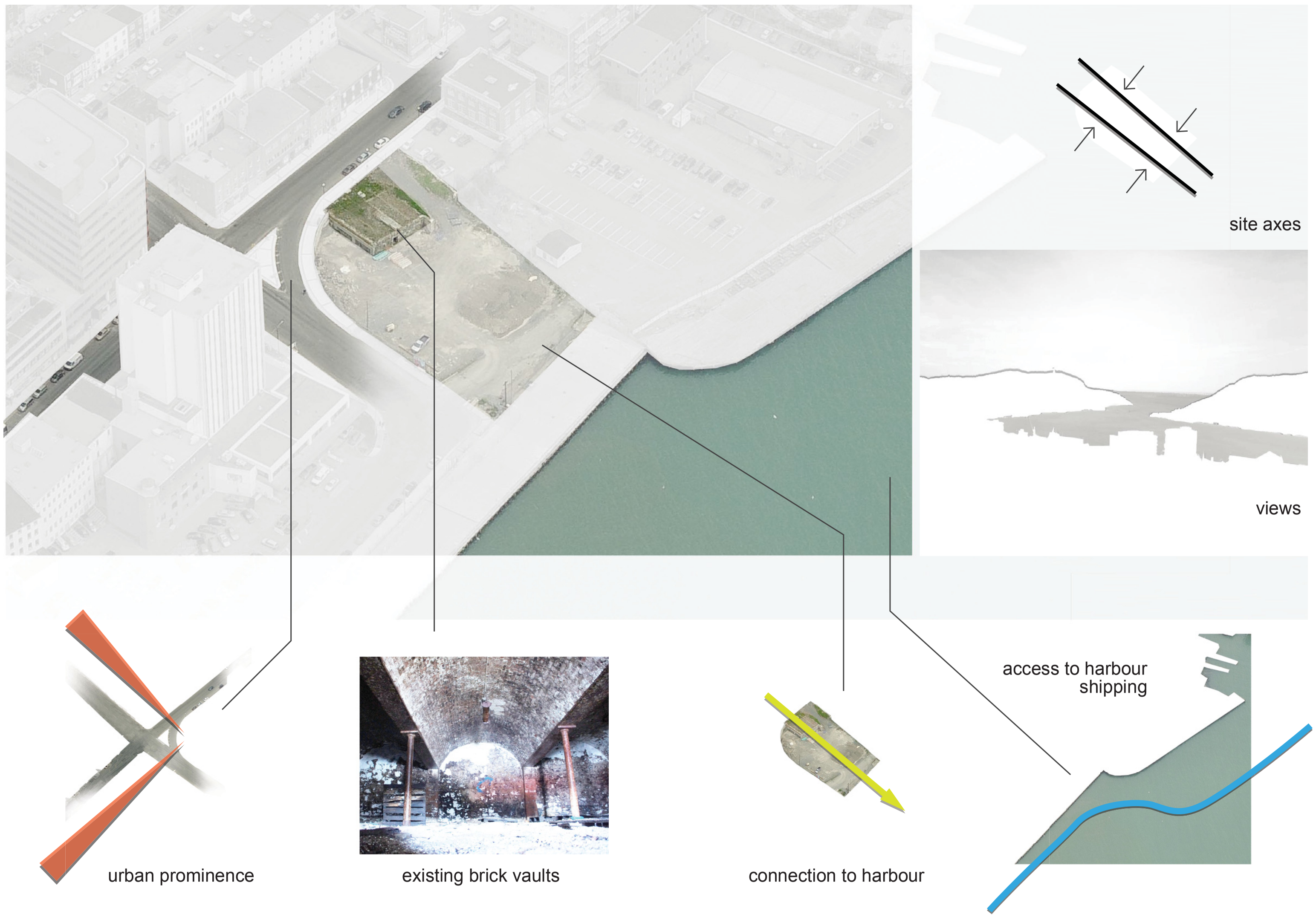
Panoramic photo of site from southwest showing Water Street (left) and harbour ‘narrows’ (right)

Throughout the location’s 500 year history many approaches to settlement have occurred. When viewing historic maps from the eighteenth century, topographical features are clearly drawn and settlement patterns can be seen as being influenced by existing conditions. As time went on and the city grew, development began to override the natural influences and began to shape the place itself. Today most of the harbour shoreline has been reclaimed and made into modern wharves. This shift from working with given information to overpowering through scale is similar to the craftsman-industrial changes described previously.

The design of the building for this site will be, as CLT is, large in scale but shall react to existing site conditions. Such conditions include its harbourfront address, views, prominence in the urban fabric, site remains, pedestrian traffic as well as environmental conditions.



Maps and diagrams showing changing features and conditions of focus over site history
(base maps from Google 2013 and Memorial University 2013)



Current site conditions of interest for thesis design
(base aerial image from Bing 2013a)

Program

The program for the design concept is primarily driven by the desire to create spaces that reflect properties and ideas developed through the preceding thesis research. A mix of complementary public use spaces including gallery spaces, event spaces, restaurant, cafe, and shops combined with office and studio spaces will be used as means to bring form to thesis explorations.

Building

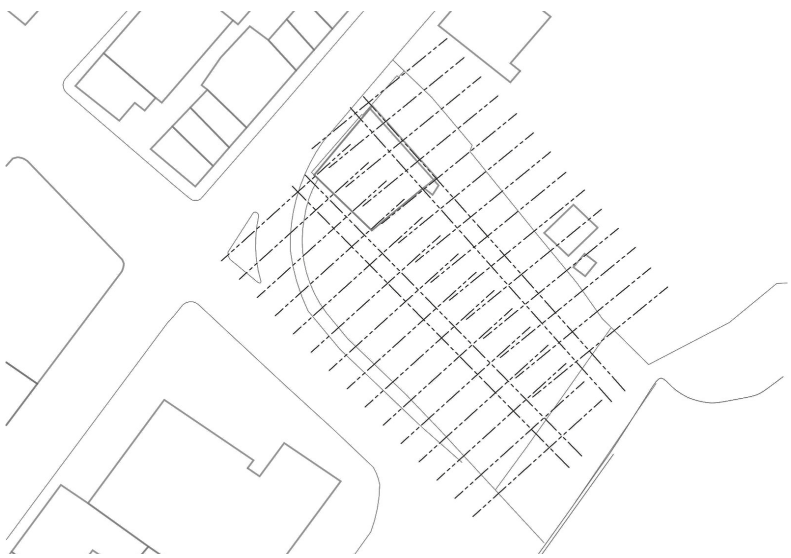
The building design concept is intended to call on ideas drawn from both the thesis research and panel prototyping. Just as lumber members were arranged based on material properties and required results, CLT panels will be arranged according to their qualities and purpose. As with the panels themselves, effective parts shall be determined and acted upon to build the final form. Relationships between building components such as floor plates and wall structure shall be examined to inform ways to bring forward a multiplicity of results in structural, spacial and system qualities.

Perspective view from Water Street of 1:100 thesis building model including grade line

Form

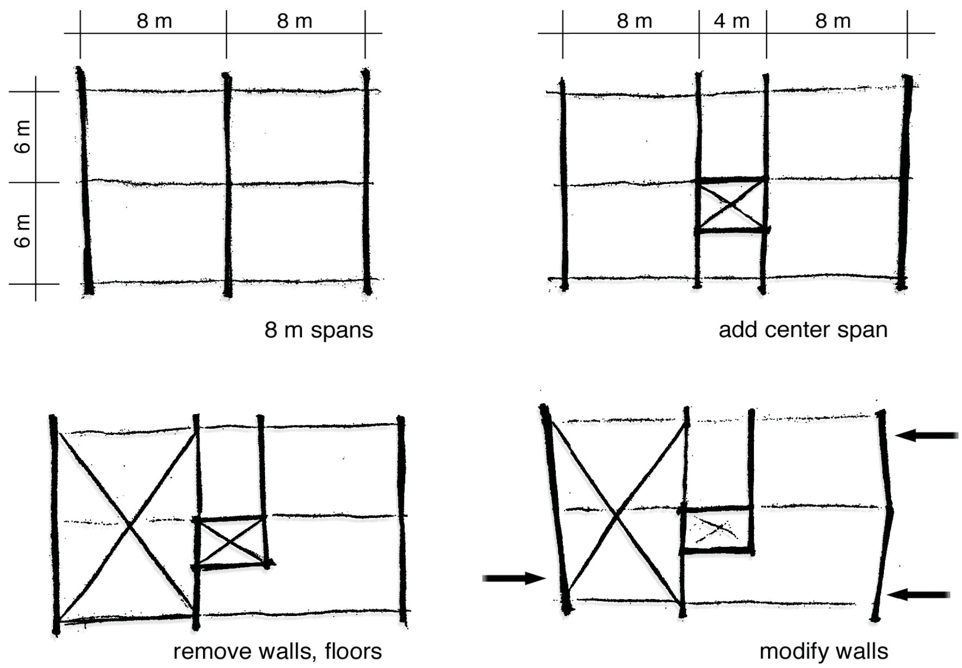
The building design itself is a seven storey, double mass with major and minor forms. The site grade has been maintained leaving both the brick vaulted foundations and retaining wall intact. A primary entrance is located on the second level and accessed from Water Street across a plaza formed by the roof of the brick vaults. On the harbour side, access to the building is on the lowest level and possible from several points.

The irregular site boundaries suggested two, slightly off-parallel longitudinal axes. 6 m structural bays are arrayed down each axis and correspond to current maximum CLT panel widths. The major form features 8 m spans extending from the central axis. This span length is a typical maximum spanning distance for CLT and is also appropriate for natural light and ventilation.



Dual axes with 6 m grid lines overlaid on thesis site

As with the integrated CLT panels themselves, the design now begins to be ‘teased apart’ for the inclusion of various features and systems. The major form’s central axis was split into a 4 m wide spine providing a service core while also expanding the overall width from 16 m to 20 m. Sections of wall along the central spine were removed to manipulate spaces for programatic functions. Once again the idea of ‘effective’ parts comes into play. Adjacent structure and adjacent system capabilities have to be considered to ensure successful spacial manipulation. A thoughtful arrangement of effective components must remain to offset exclusions needed for the desired spacial results.



Conceptual manipulation of building giving rise to formal strategy

To create large, clear-span event and gallery spaces (up 20 m x 24 m in this design), the circulation, small exhibition and service spaces on alternating levels became inhabited structure. These ‘structural spaces’ support both the floor above and the floor below while simultaneously functioning as programmed areas. In combination with adjacent floor components, the spanning walls also provide opportunities for service ‘detours’ around excluded wall and floor members.

Double height areas for event and gallery spaces were formed by the removal of sections of floor. While changing the scale of the spaces, rooms now extend and link with other event and gallery areas. The result is a system of interwoven spaces manipulating the design’s circulation and experiential qualities.

Model showing programmed structural spaces (highlighted in red) allowing large uninterrupted spaces above and below

Highlighted model section showing the interweaving of large event and gallery spaces through floors (green) and smaller cellular spaces (yellow)

The minor mass was designed in much the same manner. The overall width is narrower however and many of the spaces are smaller as well. It is in this mass that more private programmed areas are found (with the exceptions of a cafe and a restaurant).

Between the two masses a courtyard is formed. The central volume has three continuous floor spaces on the lower three levels each open to the outdoors at the ends and above. Upper levels of the masses are connected by bridges enclosed in glazed boxes. The courtyard space becomes essentially a third axis linking Water Street to the harbour.

Axis from Water Street to harbour and view of courtyard

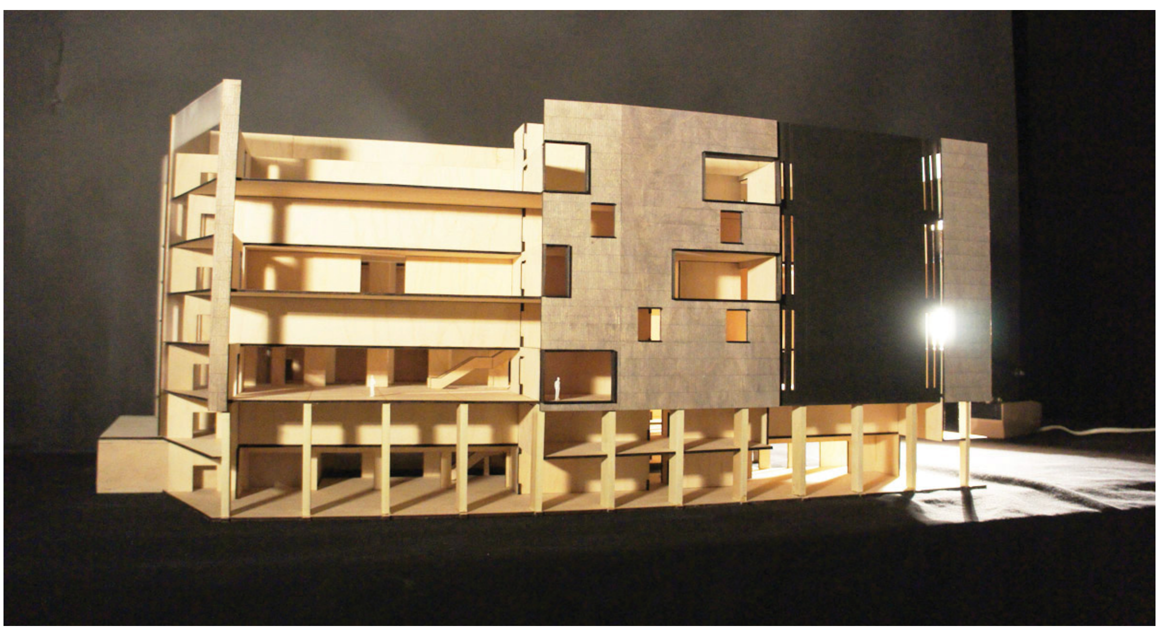
Exterior walls were then manipulated for the design. Slightly shifted and articulated longitudinal walls further respond to site boundaries. Glazed end walls were tweaked to address the prominent intersection and views. Walls within the courtyard were manipulated to address the 'harbour axis' and to allow for natural light and air penetration for the building.

The resulting building form developed much like the design of a specific integrated CLT panel. By manipulating effective and non-effective components for desired features and embedded qualities, a highly specific, multidimensional integrated building design arose.

Structure

System integrated CLT has been employed as the primary structure for the thesis building design. Because in this design the structure is space making as well, it also serves that function.

Two wall/floor construction approaches were employed in the design. Firstly, the exterior walls act as balloon structures and have floors ‘hung’ from them. The walls along boundary conditions clearly exhibit this arrangement. They run as continuous wall panels from the ground level columns up to the parapet top. Exterior walls in the courtyard are balloon structures as well although having the appearance of posts and lintels. Emergency stair and elevator shafts are also vertically continuous. The remaining interior walls are different however. They are part of a platform construction system. Each wall storey rests on the floor below and supports the floor above. Having a platform constructed interior allows floor planes to extend above or below walls when desired. This is useful for manipulating floors and walls but the platform approach benefits in this case are countered by a downside. Due to the dimensional instability of conventional CLT through its thickness, platform CLT construction typically clashes with balloon framing methods. As a result, a system integrated CLT solution was developed to remedy this situation.



Demounted model showing internal platform construction and exterior vertical balloon construction

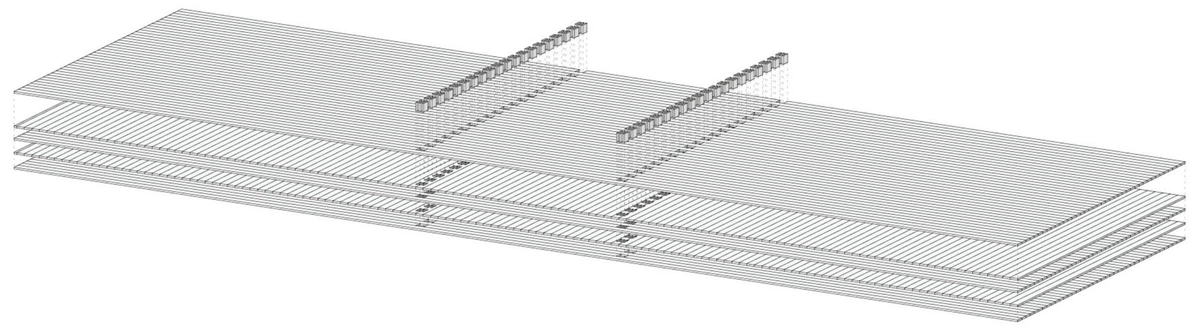
To eliminate the platform/balloon clash, a new panel type was designed. Simply put, it makes a CLT panel dimensionally stable in three directions where needed. It involves the inclusion of vertically oriented lumber members where structural loads are transferred through the panel thickness. Because wood movement along the grain is negligible, it creates points of fixed thickness unchanged by external conditions thus eliminating differential movement between platform and balloon construction. An added bonus to this is that endgrain wood is less likely to crush than crossgrain wood thereby further strengthening the result.

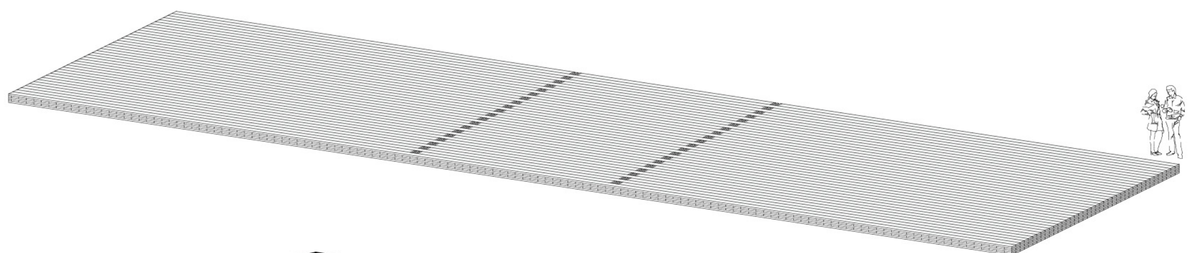
Some use of CLT within the building design as spanning beams and inhabited structural space has been described previously. This type of use fits roughly within the platform construction vocabulary.

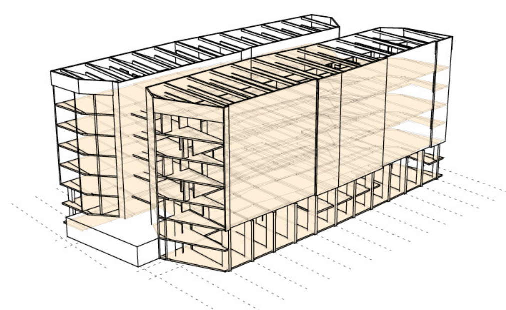
Exterior structural walls for the building design include insulation integrated within the CLT panels themselves. Voids for insulation are formed during the CLT panel fabrication and factory filled with polyurethane foam. Insulation voids are required in various panel layers to manage potential thermal bridges. Panel members that structurally bridge the main insulation layer create thermal bridges which are addressed elsewhere within the panel makeup. Smaller, supplementary insulation voids in other layers align with the wood bridging to break the thermal bridge.

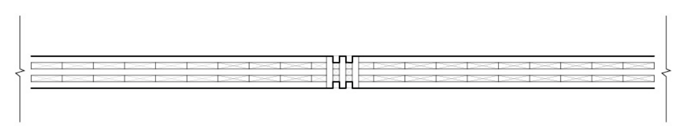
Sizes of panels employed in the building design range from smaller, common CLT dimensions up to current maximum fabrication allowances. Although shipping is often a limiting factor for panel size, it is not an issue for the thesis site. Panels dimensions are not limited to transport truck restrictions and may instead be maximum sized components delivered directly to the site by ship.

Structural panel connections include proprietary screws, interlocking wood joints and custom steel brackets.

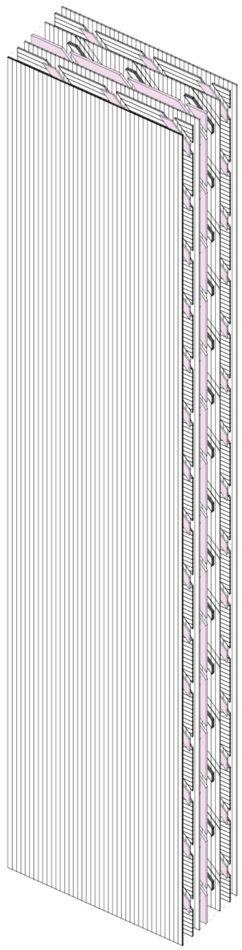


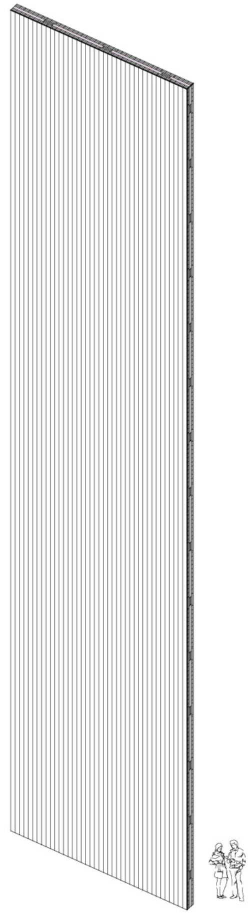


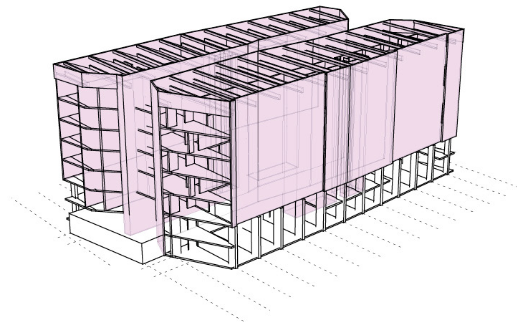


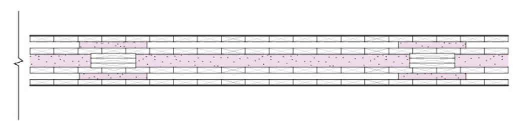


Vertical Grain Load Transfer CLT









Structural Insulated CLT

Facade

The building facade features four main approach types each addressing specific design considerations. Influenced by site variables and construction potential, aspects of CLT design and use can be witnessed in how it is employed. The structural and spacial strategies for the building design have created longitudinally oriented forms with walls and floors wrapping the long sides while leaving open ends.

To address the urban condition and harbour views, end walls of the two building masses are primarily curtain wall glazing. A glimpse into the building's network of structure and space is available through the highly porous ends. Transparency from Water Street is intended to both express and invite building use. Circulation areas and gallery 'ante chambers' hint at what lies beyond. Opposite, on the harbour side, curtain wall is used to provide expansive views of the harbour and surroundings. The glazed spaces with views to the harbour include public gathering areas, public circulation, a cafe and a restaurant.

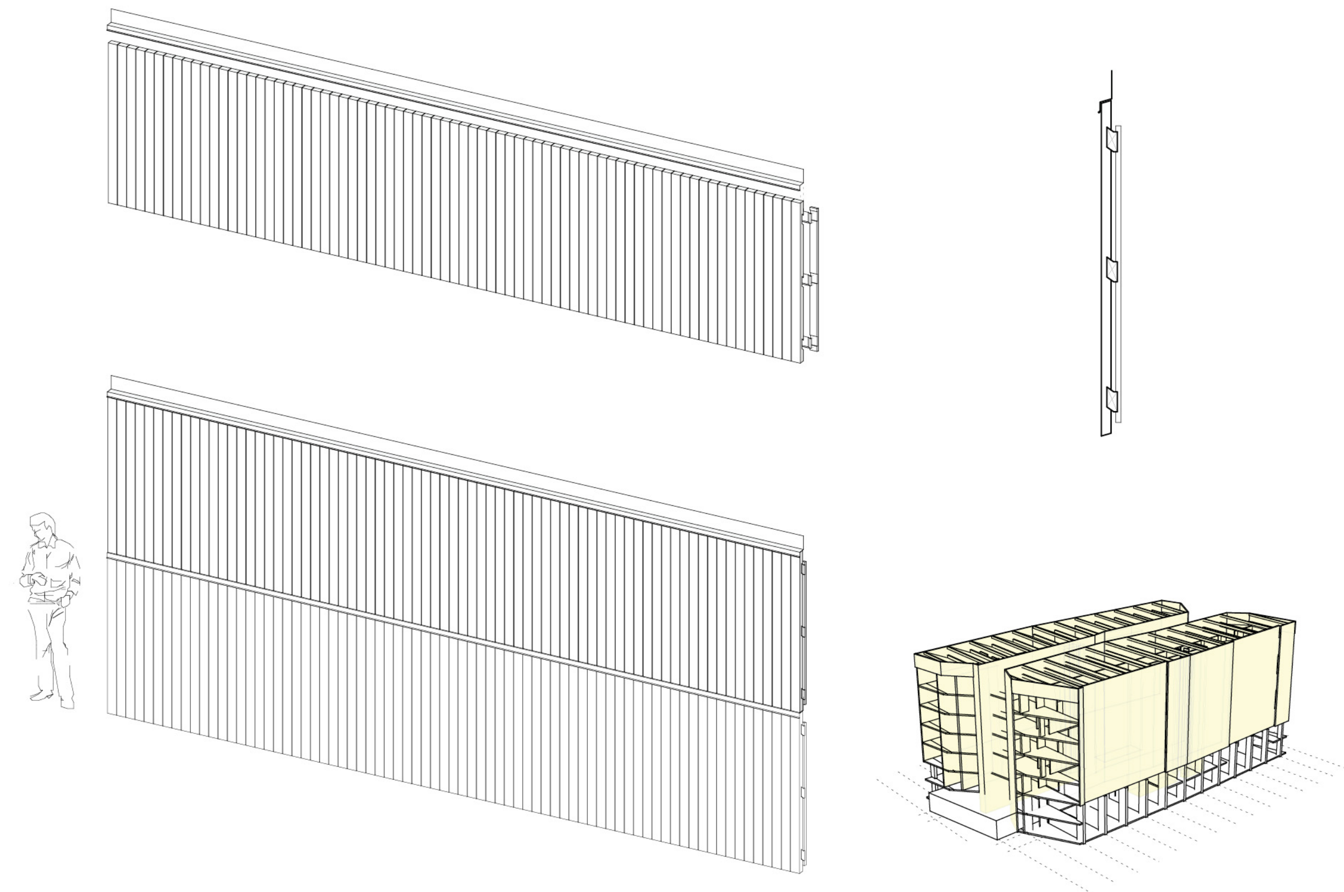
The visually porous building end walls viewed from Water Street (left) and harbour (right)

In contrast to its porous ends, the building design has two large solar walls on the south long wall. Massive, balloon structured, insulated CLT panels are charred black for solar gain and encased behind an expanse of glass. This creates two shallow solar chimneys intended for solar gain and return air collection. Tall slit windows are the only penetrations in the panels. These almost uninterrupted planes of blackened wood also control light for gallery spaces directly behind. The narrow windows allow light to wash along gallery end walls while the remaining masses block direct southern sun.

Interior and exterior views of gallery volumes and solar wall

The remainder of the south wall plus the entire north long wall are structural insulated CLT panels clad over with a CLT cladding system. This cladding system is a very teased apart type of CLT. Vertical cedar boards make up the exterior side of the panel. The boards are roughly 1.4 meters in height and 200 millimeters wide by 40 millimeters thick. A 12 millimeter gap between the boards allows for movement and airflow. Bottom and top edges of the vertical cedar boards are profiled to overlap like shiplap siding. Behind the surface boards are horizontal battens, up to 10 meters long, keyed into the backside of the cedar. The horizontal battens are in turn notched into vertical battens spaced 1 meter on center. The result is a panel system which is fairly light in construction, large in scale (1.4 m x 10 m) and incorporates integral drainage plane features.

Perspective view from east showing cladding and glazing strategy for north long wall



Cladding CLT

For the exterior walls around the courtyard, a hybrid structure/curtain wall system is employed. To allow maximum light penetration from the central space, the CLT structure is reduced to a minimum. Continuous glazing secured on mounting pins stretches over the entire 'post and lintel' structural walls. A great openness to the courtyard is achieved as well a clear visual link between the main circulation spaces of the two opposing building masses.

Continuous glazing over CLT structure of the central courtyard

Hollow Core CLT

Within the building interior, the most abundant panel type is hollow core CLT. It is an integrated air ducting system incorporated primarily into floor panels. Its basic arrangement features air cavities flanking spanning members which have been sandwiched between two CLT skins. The air cavities may be lined with tear resistant foil as a means to control moisture and debris buildup. Walls may also have cavities linked into a comprehensive hollow core CLT system.

A more specific design is used for the thesis building. Due to some discontinuities from wall exclusion for spacial gain, alternate supply strategies were needed. Main CLT trunks run air vertically up through the building at various points. At each level, air can flow out through gaps in the trunk into floor plenums. These plenums run down the length of the 4 m spine. Because the structural requirement is less for the 4 m span, no internal structure is needed between the two CLT skins thus allowing for open air spaces. Running perpendicular to the plenum are the internal spanning members and flanking air cavities. A long tapering 'island' within the plenum generates even flow out into the cavities feeding air supply grills located in the floor panels.

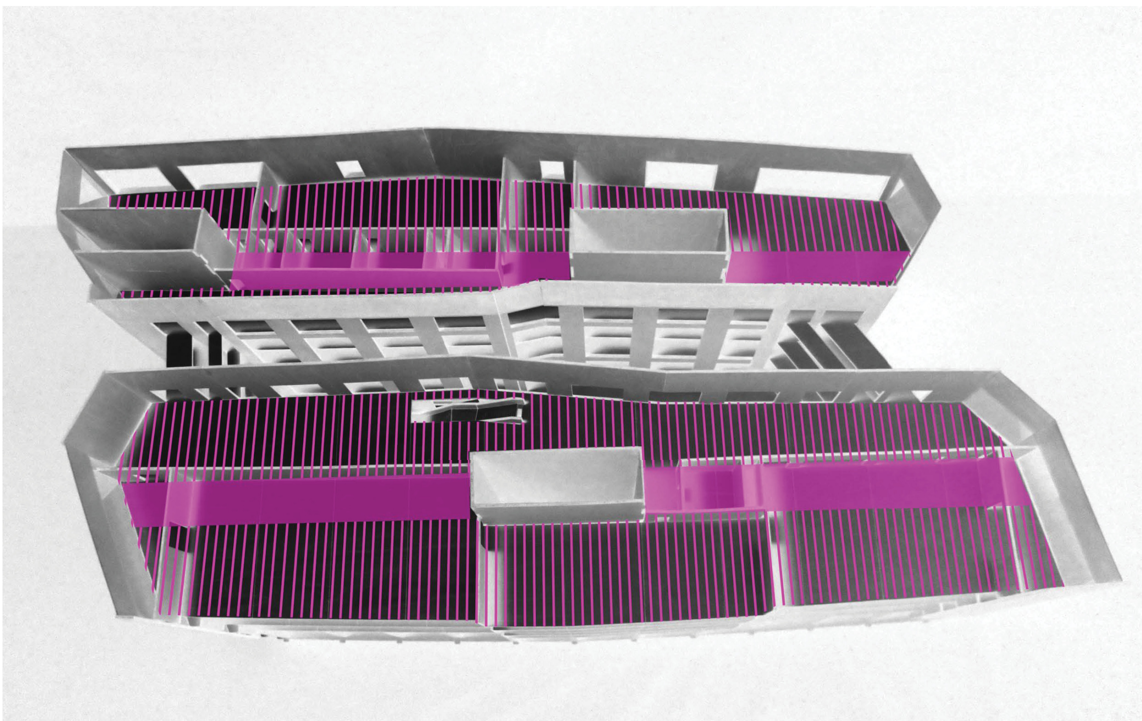
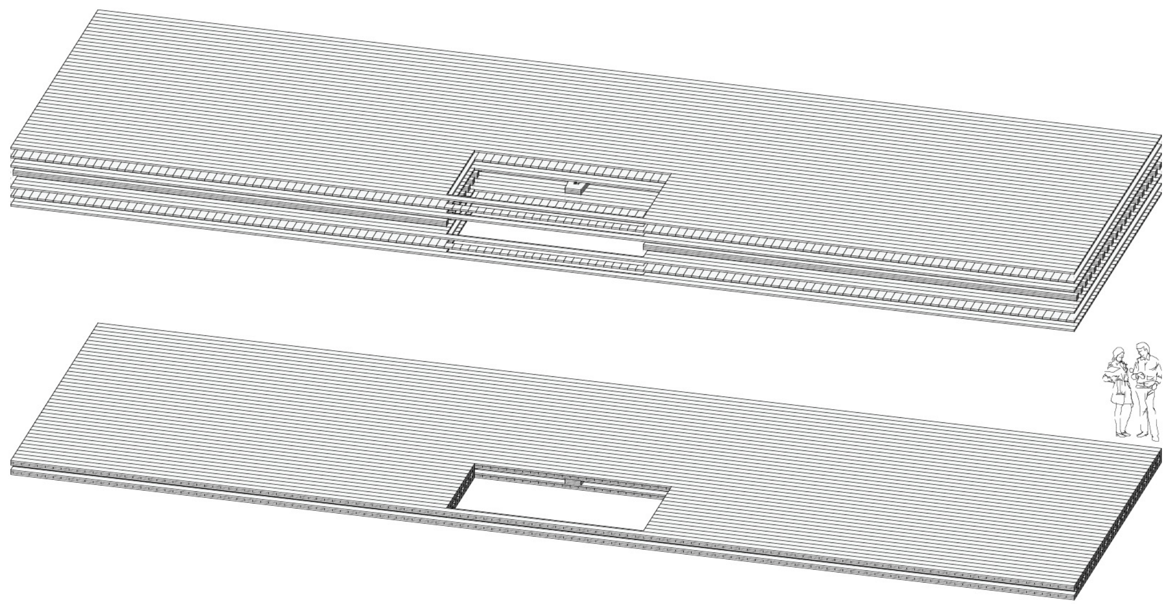
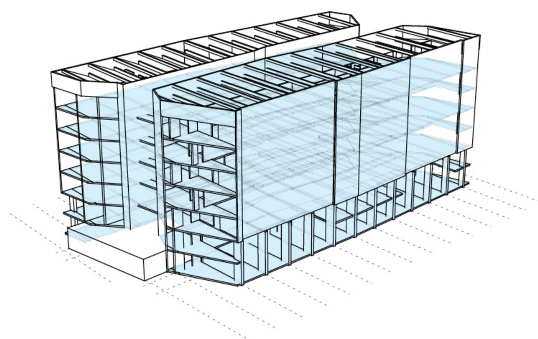
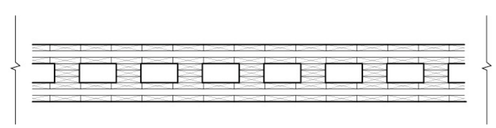


Diagram of plenums running along central spines with perpendicular branching ducts

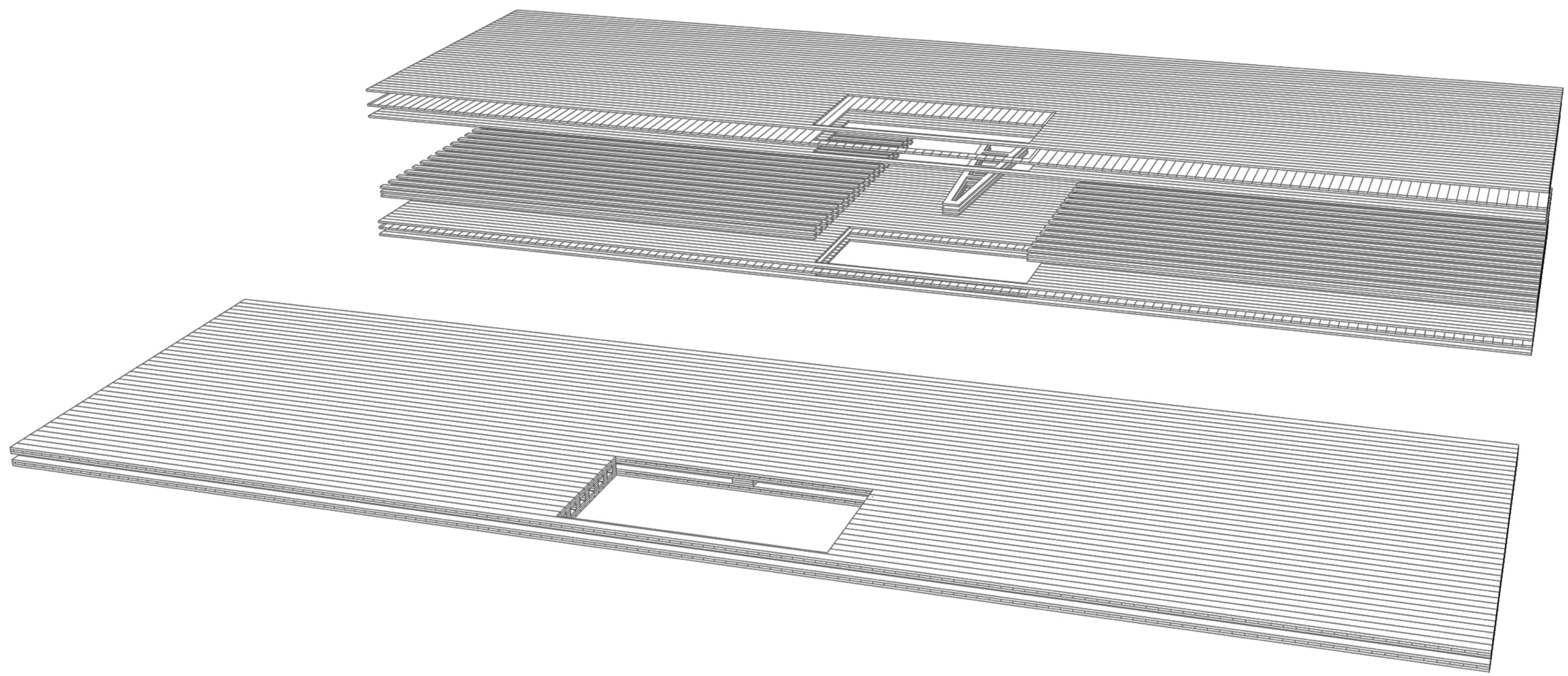
Return air is exhausted to the solar chimneys or to integral wall ducts inside the exterior walls. Electrical and plumbing chases may also be incorporated in a similar fashion as the hollow core CLT design.



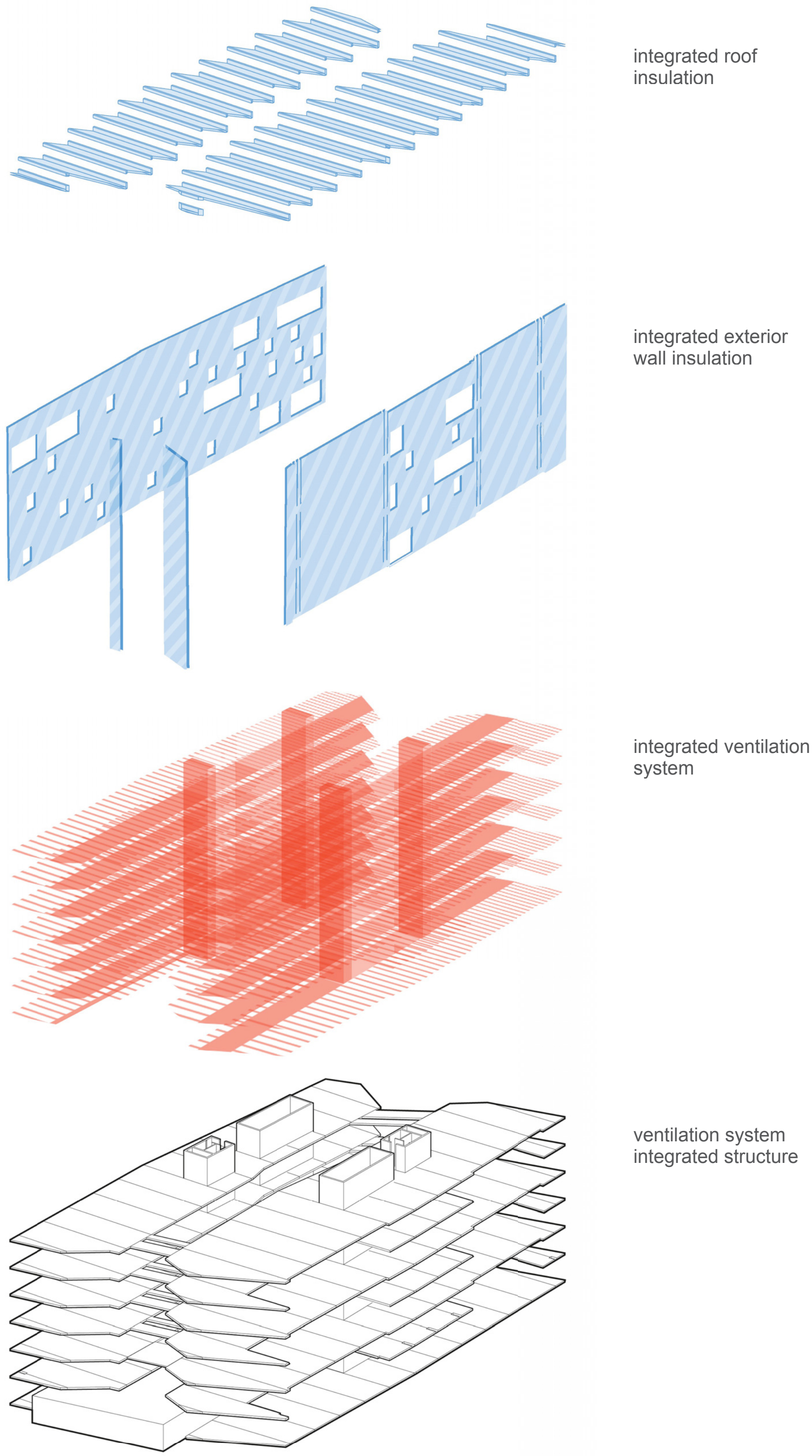




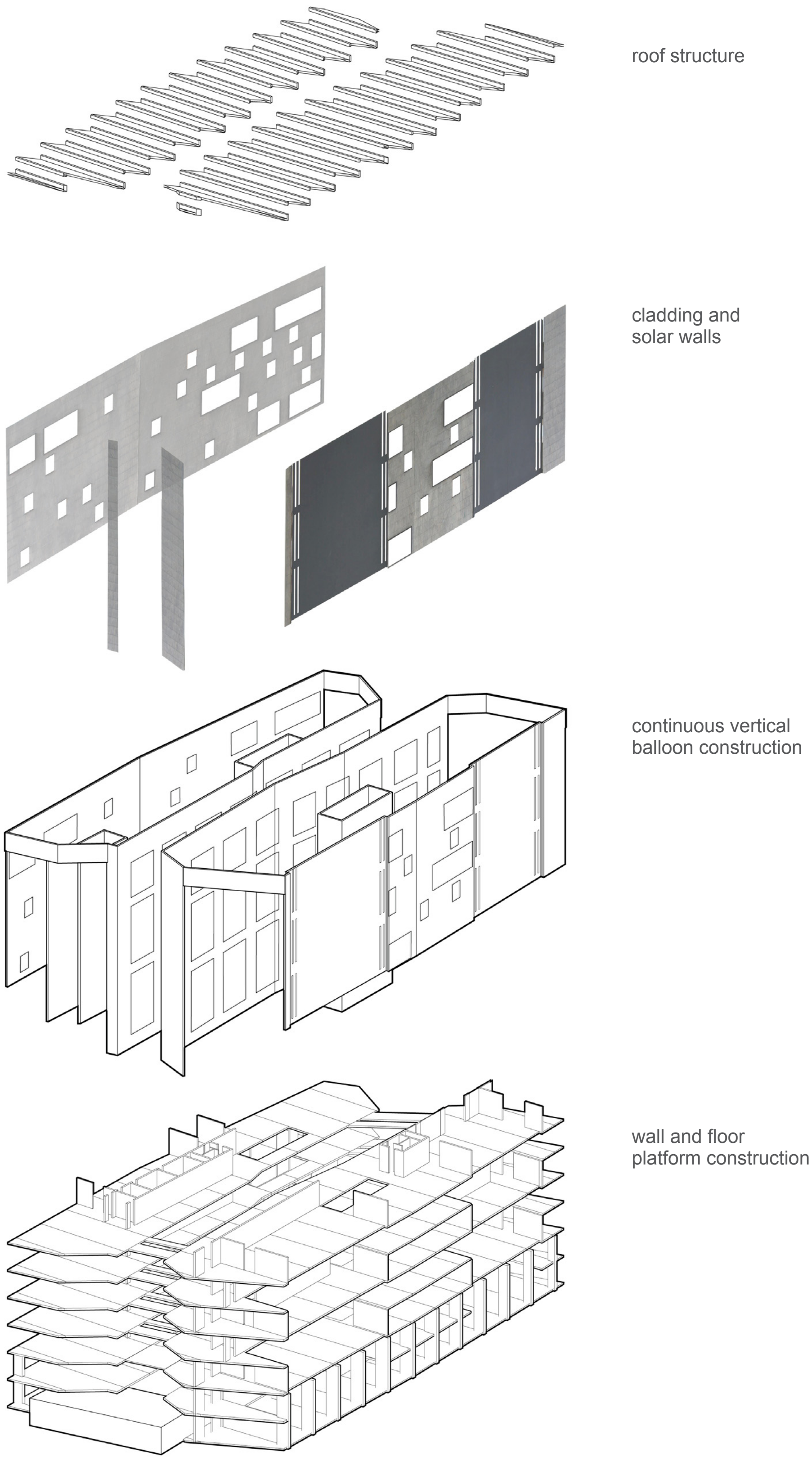
Hollow Core CLT



Exploded axonometric of Hollow Core CLT showing vertical chase penetration, central plenum and branching duct voids



Exploded axonometric of thesis building showing insulation and ventilation strategies



Exploded axonometric of thesis building showing roof, cladding and structural strategies

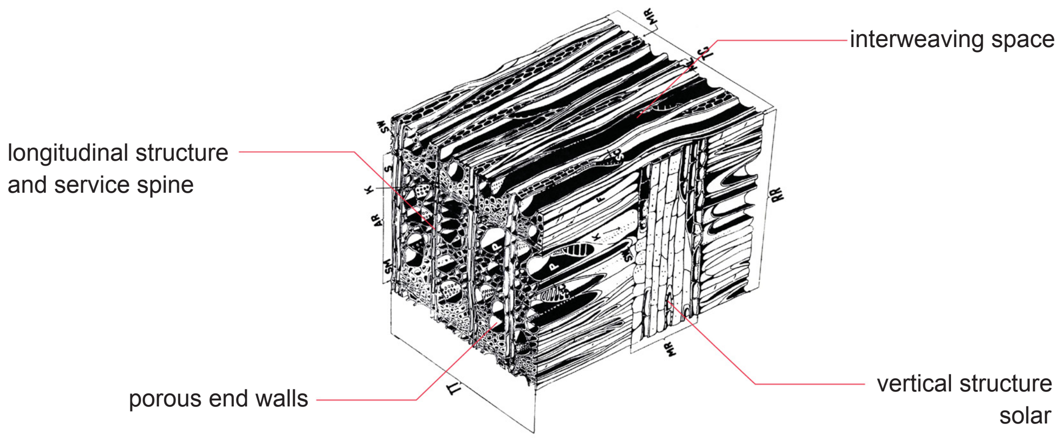
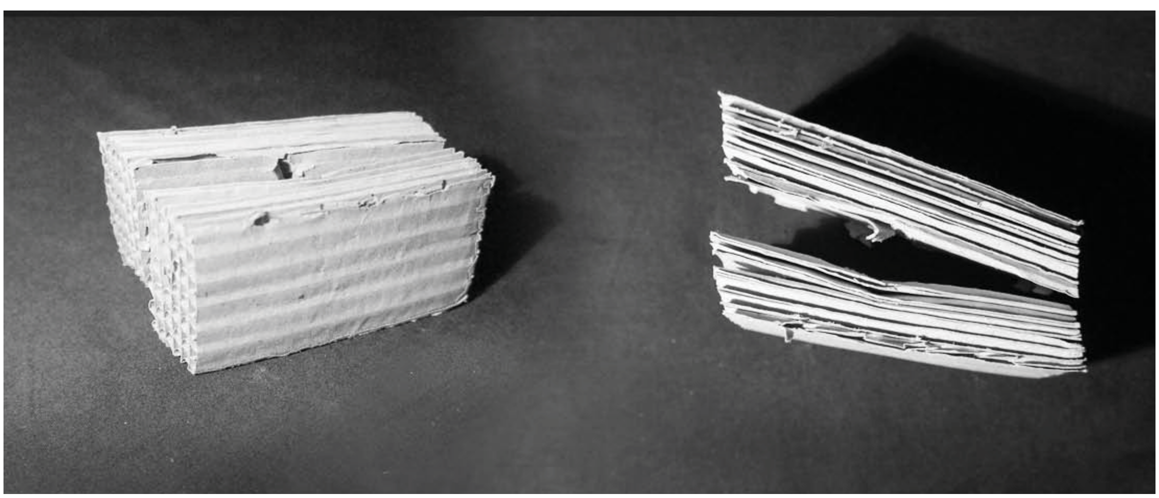
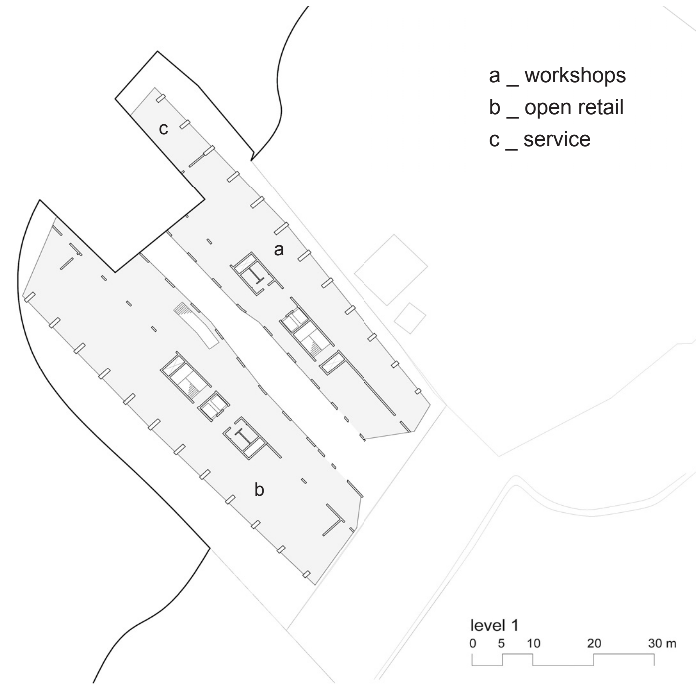
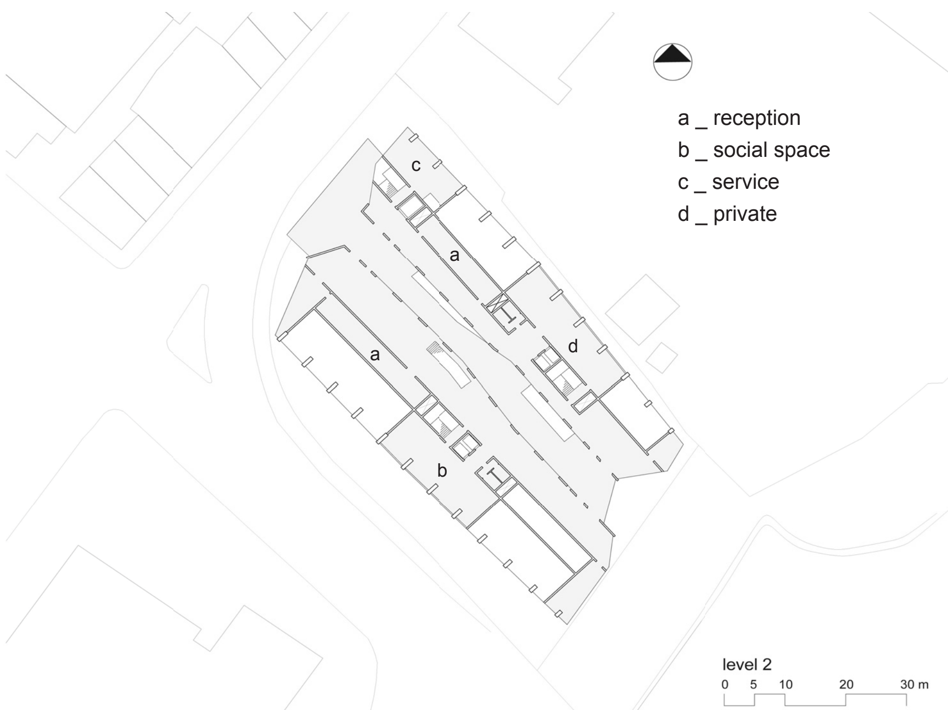


Image of microscopic wood structure as conceptual structural and spacial form
(base image from TRADA 2013)



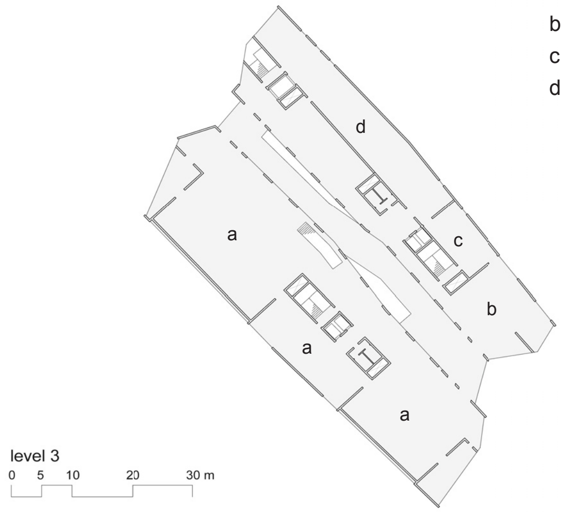
Conceptual structural and spacial form expressed as cardboard massing model



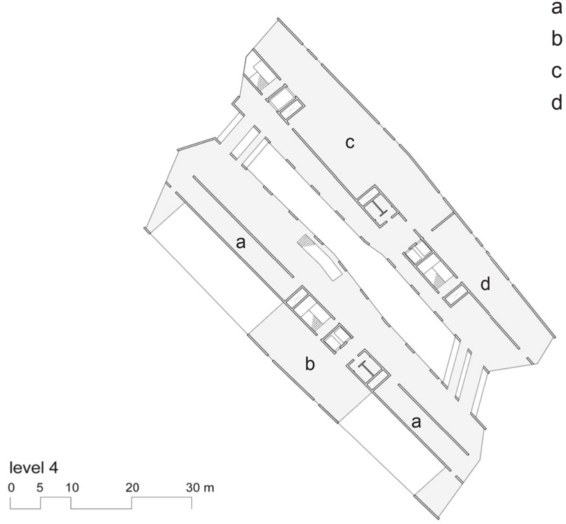


Plans including grade cut at level one and site at level two

a _ event space
b _ cafe
c _ service
d _ private

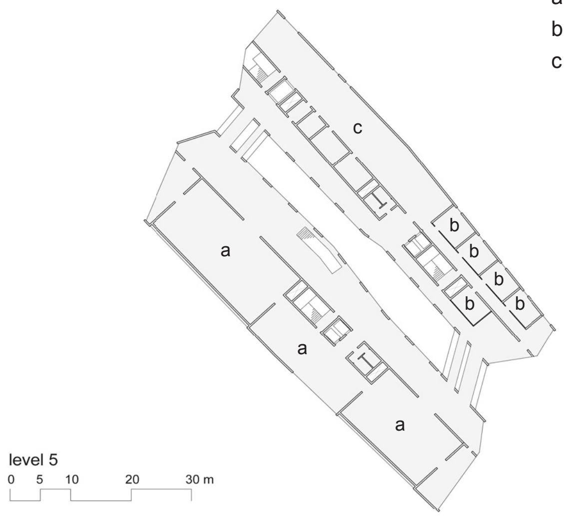


a _ picture gallery
b _ gallery
c _ storage
d _ private

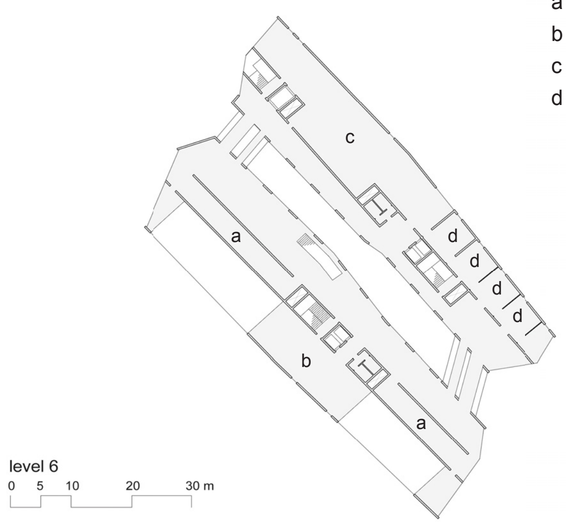


Plans of levels three and four

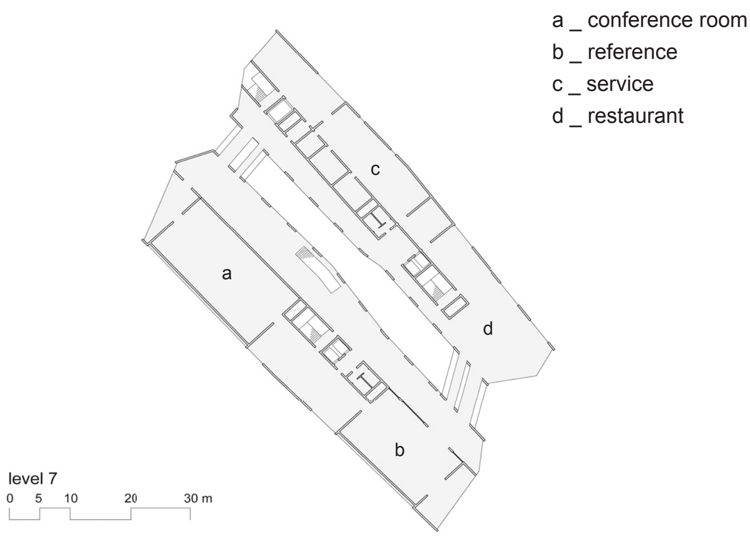
a _ gallery
b _ office
c _ storage



a _ picture gallery
b _ gallery
c _ open workspace
d _ studio



Plans of levels five and six



Plan of level seven

Aerial view from west showing building massing (background from Bing 2013b)

CHAPTER 7: CONCLUSION

We now see the emergence of an Architect-Craftsman in the form of a digital designer/maker team. This novel distinction bridges the designer/maker separation traditionally at the core of the architectural profession. What makes such a condition possible is the use of digital technologies for continuity between design and fabrication processes. In addition, digital production methods allow for both the specificities and scale required in modern, custom building components and architectural constructions alike. Keeping in mind these ideas, an architect-craftsman must approach design and making in ways which are true to the essence of craftsmanship.

A craftsman is fluent in the in the language of appropriate tools employed for making and designs with this knowledge in mind. The digitally engaged architect-craftsman must also design within the language of tools involved. New architectural design and fabrication methods are steadily emerging and should be critically explored to discover their full potential. This thesis showed how Cross Laminated Timber and its production methods could be analyzed in terms of ‘craft’ to suggests new forms and new ways of making. Concepts of effective yield, embodied and embedded information and emergence proved useful for my thesis exploration of CLT. By finding relevant analytical ideas, both related to and at the core of craftsmanship, System Integrated Cross Laminated Timber was developed, a fabrication method proposed and the material ultimately employed in a building design.

The proposed fabrication method for System Integrated CLT makes use of a fuller range of digital technology than is presently employed for the current CLT form. The result is a new ‘digital language’ for CLT which pushes ideas about its making and use forward into a technologically comprehensive state. This new language is expressed through all material and building scales as a result of embedding specificities and properties at the lumber, panel and building levels. Structural and building system strategies, formal expression and experiential qualities are all influenced by the material and process itself. The full collection of parts come together tectonically and systemically to make the whole a complete, integrated system of systems.

Moving forward from the core concepts of this thesis, one can see the opportunity for a broader application of ideas developed in the work. As an analytical approach for investigating material, process, and building in terms of ‘abstract’ applicable concepts, rethinking current practice can be applied to architectural technologies beyond those of CLT. As the architectural designer/maker gap has been bridged through new thought, architect/material scientist gaps may be bridged as well. In recognizing this, an architect has the potential to perform as a material, process and building designer and maker; it is now the imperative of an architect-craftsman to do so.

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