OFF-SITE STUDIES

SOLID TIMBER CONSTRUCTION

PROCESS
PRACTICE
PERFORMANCE

Forest Products Laboratory
Research Working For You

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INTEGRATED TECHNOLOGY IN ARCHITECTURE CENTER
UNIVERSITY OF UTAH COLLEGE OF ARCHITECTURE + PLANNING

THE UNIVERSITY OF UTAH

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CONTENTS

EXECUTIVE SUMMARY

ABSTRACT

This project evaluates off-site solid timber production processes in the international solid timber industry. The Solid Timber Construction (STC) projects documented herein provide a test bed to evaluate project performance metrics attributed to off-site construction. This study also evaluates the contingent qualitative environmental, organizational and technological contextual factors related to STC. The study therefore:

1. Investigates and documents STC projects to identify successful performance metric parameters: economics, schedule, scope, quality, risk, and worker safety;

2. Compares this data to traditional site built construction to determine the estimated added value or negative impact of STC;

3. Identifies qualitative contextual parameters including environment, organization and technology for successfully developing STC methods;

4. Creates a model for data gathering for STC stakeholders to report their own performance parameters and thereby create a robust database of off-site projects in the future; and

5. Synthesizes holistic best processes and practices guide for the industry looking to engage in STC work.

KEY FINDINGS

Quantitative Analysis

Cost	• 4% Savings
Schedule	• 20% Savings
Quality	• 3.7 Average Change Orders
Safety	• 0 Reported Safety Incidents

Qualitative Analysis

Why Chosen	• Speed of Construction • Wood First Initiative • Sustainability
Software	• AutoCAD: 26% • Cadwork: 17% • Sketchup: 15% • Other: 42%
Challenges	• Code Approval • Acoustics & Connections
Successes	• Short Build Time • Innovative Material • Market Exposure
Lessons Learned	
ADVANTAGES	DISADVANTAGES
• Speed • Weather Versatility • Raw Material • Carbon Reduction • Remote Locations • Labor Costs • Weight • Precision • Safety	• Knowledge & Labor • Research • Logistics • Planning • Acoustics & Vibration • Job Displacement • Code & Permits • Wind • Component Flexibility

Return on Investment *See pg. 42-44*

25% Schedule Reduction	$5.81/SF Average Savings
50% Schedule Reduction	$10.93/SF Average Savings

NEXT STEPS

During the study, next steps for continuing construction performance evaluation of STC were identifed.

1. Develop alternative methods of comparative analysis including:

    a. Performing an STC bid and schedule outline for a completed site built project based on as-built and specification documents; and

    b. Evaluating a side by side comparison of a stick-framed and STC projects that are near similar (i.e. hotel chain built at the same time in different locations).

2. Continue to maintain metrics standards that are consistent with ASTM, NIST and ISO.

3. Collect labor hours in the STC industry, and construction industry more broadly to determine productivity in construction.

4. Conduct a survey annually to seek current benefit and barrier perceptions of STC in the industry.

5. Continue to codify analysis areas that others are working toward, and prioritize those areas that most impact the uptake of off-site construction.

6. Develop an implementation guide for owners, designers, and fabricators to provide how-to knowledge of off-site delivery.

INTRODUCTION

PURPOSE

Solid timber construction (STC) refers to different types of massive wood planar or frame elements used for walls, floors, roofs, partitions and core elements of a building. Construction with solid timber elements optimizes the inherent structural behavior of wood, creating a more homogeneous structural product. Several different factors make STC appropriate today.

Global climate change, increasing water and air pollution and the rapid decrease of non-renewable resources has moved the construction sector to utilize materials that are low carbon emitting or carbon capturing in their life-cycle, and therefore, less environmentally harmful. Expanding the use of construction materials with low embodied energy from renewable resources that have the capacity to sequester carbon in the structure of buildings will help to reduce our global impact on the environment. These qualities make STC an attractive and viable option in the 21st century.

STC is an off-site fabricated element. Off-site fabrication is the manufacture and pre-assembly of building elements before installation at the construction site (Sciences, 2015).Off-site fabrication is able to leverage the advantages of a modern factory setting. Producing building system elements with contemporary advanced measurement devices and manufacturing methods provides multiple advantages:

- Decrease of material waste because of precise manufacturing process.
- Decrease of on-site time and energy waste by using pre-assembly systems.
- Optimizing material value, e.g. modern measurement devices including acoustic grading and machine grading are able to predict the grade of timber to provide greater value.
- Adding value by utilizing lower quality timber in higher value application.

The added value of STC, although conceptually strong, has yet to be significantly demonstrated through analysis. The lack of qualitative or quantitative data on STC has been identified as a barrier to its adoption in North America. As a disruptive technology, without a compelling case for its use, STC will have difficulty increasing its market share in the traditional construction sector. In addition, there does not exist a standardized method for collecting data on STC projects in order to build an empirically evidenced argument. Finally, there is a lack of qualitative information about the context in which successful STC is realized including addressing issues of project delivery.

STC includes glued and non-glued systems of construction including: (*See Figure 1*)

Glued STC

- Glue-laminated timber (GLT);
- Structural composite lumber (SCL) including Laminated veneer lumber (LVL), Parallel strand lumber (PSL), etc.;
- Cross-laminated timber (CLT);

Non-glued STC

- Dowel-laminated timber (DLT);
- Nail-laminated timber (NLT) and cross-nail laminated timber; and
- Interlocking cross-laminated timber (ICLT).

CLT and other STC systems also have the potential to utilize traditional structural lumber and other woody biomass from the National Forests such as hazardous forest fuels, beetle killed trees, and salvage trees. By utilizing these trees they have the potential to reduce the cost for treating hazardous fuels and the removal of other woody biomass in our forests.

Figure 1

Types of Solid Timber

Credit:Centre for Off-site Construction + Innovative Structures, Edinburgh Napier University

Bridport House
Photo Credit: Karakusevic Carson Architects

TABLE 1 - BACKGROUND LITERATURE

The following is a list of literature resources used to provide a basis for this report. (See references section for citations)

USA Journal papers, articles, reports on solid timber
McGraw Hill study (2011)
Reports by FPInnovations, WoodWorks, and APA
UK studies as precedent
Standards for data collection: ASTM, ISO, NIST

TABLE 2 - AUDIENCES

This report is aimed at the following audiences in the construction industry.

Market Sector Audiences	Healthcare Housing/Dormitory Hospitality Retail Office
Stakeholder Audiences	Owner Design Team (A/E) GC/CM Solid Timber Manufacturers Regulatory Bodies

TABLE 3 - CASE STUDIES

Case studies included herein are diverse in region and context.

PROJECT	LOCATION
Bridport House	Hackney, London, UK
Bullitt Center	Seattle, WA, USA
Carlisle Lane Lofts	Waterloo, London, UK
Centre for Creative Competitive Design	Bedforshire, UK
Elkford Community Centre	Elkford, BC, Canada
Fort McMurray Airport	Fort McMurray, Canada
Forté	Melbourne, Australia
Holy Trinity Primary School	Richmond, London, UK
Massive Living	Graz, Austria
Open Academy	Norwich, UK
Smart Price House	Hamburg, Germany
SmartLIFE Centre	Cambridge, UK
Tamedia Office Building	Zurich, Switzerland
The Long Hall	Whitefish, MT, USA
UBC Earth Systems Science Building	Vancouver, Canada
UBC Okanagan Fitness & Wellness Center	Kelowna, BC, Canada
Via Cenni	Milano, Italy
Wagramerstrabe	Wien, Austria

METHODS

CASE STUDY METHOD

This project utilizes a case study method. The case study method is a common strategy used in built environment evaluations wherein projects are identified and documented for quantitative and qualitative data through interviews and literature review. The case study solid timber project pool has been established in consultation with the Advisory Board. The selection of the 18 cases documented are based on the following:

- Access to available archival data and willingness of stakeholders to participate and offer additional data. The pool of projects started with dozens of samples, however, some project stakeholders were reluctant to share data. The pool of this study consists of projects for which stakeholders were forthcoming with information;

- Diversity of project sizes, locations and building types in order to see STC across sectors, countries and cultures; and

- Culturally significant buildings were selected based on architectural impact. The goal of the study is to demonstrate how STC performs with respect to different building types, sizes, and delivery methods.

A ranking system considering these 3 factors was devised and provided a rudimentary process for determining the cases.

Each case study was developed by gathering data from the architect, general contractor or construction manager, and the solid timber fabricator and/or supplier. A questionnaire was developed and peer review edited to identify relevant quantitative data including cost, schedule, scope, quality and safety for the STC case studies. This was disseminated online and through PDF response form. Responses were limited and therefore follow up interviews were conducted to gather additional quantitative data. During the interviews, qualitative questions were asked to determine the context for successful STC deployment. The sometimes limited information provided led to the exclusion of some case studies. In total, there are 18 case studies, and 11 of them have substantial contributing cost and schedule information. From these 11 cases studies, 7 of them have direct traditionally built projects that are compared in schedule and cost.

DATA GATHERING METHOD

TABLE 4 - QUANTITATIVE DATA

Gathered through online literature, phone interviews and email response

General Information	• Geographic Location • Site Context • Gross S.F. • Building Footprint S.F. • Number of Stories • Number of Stories in Solid Timber • Volume of Solid Timber Used • Primary Program (i.e. housing, commercial, mixed-use, healthcare) • Miles from factory to site • LEED Rating, if any
Cost Data	• Capital cost • Design cost • Construction cost • Solid Timber contract cost
Schedule Data	• Projection Duration • Construction Start Date • Project Completion Date • Solid Timber Factory Time • Erection time on site • Design Duration
Quality/Safety Data	• Change orders associated with solid timber • Safety incidents • Fatalities • Labor Hours*

**Labor hours information was not recorded or available from respondents*

TABLE 5 - QUALITATIVE DATA

Gathered through phone interviews and email response

- Why was solid timber construction used on the project?
- How was the structure of the team unique because STC was used?
- What type of solid timber was used? (CLT, Glulam, LVL, etc..)
- What digital software was used on the project?
- Were there any major obstacles that had to be overcome?
- What were the greatest successes of the project?
- What would you do differently next time?
- What were the lessons learned from this project?

UBC Earth Systems Science Building
Photo Credit: Martin Tessler

COMPARATIVE METHOD

Data from the STC projects was compared to benchmark project data supplied by Cumming Corp., a cost consultancy firm. The data for both the STC cases and the traditional comparison cases have been normalized to the first quarter of 2014 in US Dollars and Washington, DC as the location. Units of cost are calculated in $USD/SF and it is assumed that in all of the traditional benchmark construction projects in comparison use a design-bid-build delivery system. When possible, estimates for the comparisons are based on actual items of work. When data has not been available, precedent values from other projects have been interpolated for these comparative projects. Unit costs are based on current bid prices in Washington, DC with subcontractor overhead and mark-ups included. General Contractor overhead and profit has been separated.

The values determined were based on the probability of cost of construction at the programmatic design stage. The following parameters are compared using the Cumming Corp. database of projects in traditional construction. 7 of the STC projects for which data was gathered were appropriate to draw comparisons regarding cost, schedule, quality or safety.

For estimating the values, the following sources have been referenced:

- Davis Bacon Wage Rates
- RS Means Geographical Indices
- RS Means Standard Hourly Rates for Construction Industry Cumming Corporation Internal Economic and Market Report

The items not covered in this comparison include: hazardous material abatement, utility infrastructure improvements, design/consulting fees, building permitting, testing and inspection fees, and land acquisition costs.

The development of the data-gathering model has been in peer review with the National Institute of Building Sciences, Off-site Construction Council. ASTM and ISO standards for construction data referenced metric parameters for the model.

RETURN ON INVESTMENT METHOD

By employing STC, the cases in this study reduced their construction time by an average of 20% when compared with traditional construction. *Figure 23* shows the time of construction compared to their traditionally constructed counterparts. To put this reduction of time in terms of cost, a return on investment study was performed to account for the time saved by STC.

The ROI leveraged three discrete developer pro-formas for a retail, office, and charter school building type respectively. The developer data was assessed using a schedule improvement of 25% and 50% faster than the actual schedule. This did not include the financial benefit of early returns on operational business such as sales, lease rates, or educational impacts. It was a construction duration cost benefit only. The buildings included in the pro-formas are finished structures located in Salt Lake City, UT. All metrics are represented in that geographical location as well.

The pro-formas include four sections:

1. The analysis of the total build, the build time reduced by 25% and then reduced by 50%;
2. The cost of construction;
3. The cost of the construction loan;
4. And the generated income. Market rate numbers are based off of the Newmark Grubb Acres 2014 Year End Report. The Rental Income numbers are based on the presumption that the building will be 100% occupied reflecting the highest possible opportunity for income.

LIMITATIONS

This study is limited in several ways. A number of the case studies were somewhat dated with one being completed nearly 10 years previous to the publication of this report. This presented a few challenges such as: stakeholders having difficulty recalling information, key individuals that may have left an organization for a different company, or companies simply being dissolved or merged with another company. Also, a number of stakeholders were unwilling to disclose information about the project due to knowledge they had gained during the process that they consider to be company intellectual property.

The traditional site built comparative benchmark projects were also limited. The study called upon the database from Cumming Corp., a cost consultancy firm that in some cases did not have similar projects by which to compare to the STC cases. In any event, identifying like for like specified buildings is not possible. Alternative methods of traditional build and STC comparative analysis are recommended in the conclusion to this report on pg. 45.

The return on investment study also needs more samples to make a significant claim as there were only 3 pro-formas from 3 unique developers referenced.

TABLE 6 - LIMITATIONS

Limitations to the methods included in this report.

Case Studies	• Time Frame • Lack of information or willingness to provide information from stakeholders • Companies being dissolved or merged
Comparative	• Database of projects limited • Difficulty to match constructed buildings like for like specification
ROI Study	• More samples needed (3 included)

STUDY

QUANTITATIVE

GENERAL

This study asks participants the following general information questions:	Figure #
When was the project completed?	*2*
What is the building type?	*3*
What is the context location of the building?	*4*
What was the project delivery method?	*5*
What is the total gross square footage?	*6*
What is the size of the building footprint?	*7*
How many stories?	*8*
What type of solid timber was used?	*9*
How many stories were built using solid timber?	
What was the distance from the solid timber factory to the site?	*10*
What was the volume of solid timber used?	*11*

This section includes all original 18 case studies with as much information gathered as possible. However, information was left out of the study when it could not be located through literature or interviews.

Our method to find case studies attempted to gather the most diverse building types. See *Figure 3*. These case studies range from 1,722 SF to 182,986 SF (*See Figure 6).* These metrics served as a basis to further explore the importance of the inclusion or exclusion of building types and square footages in future studies.

YEAR COMPLETED

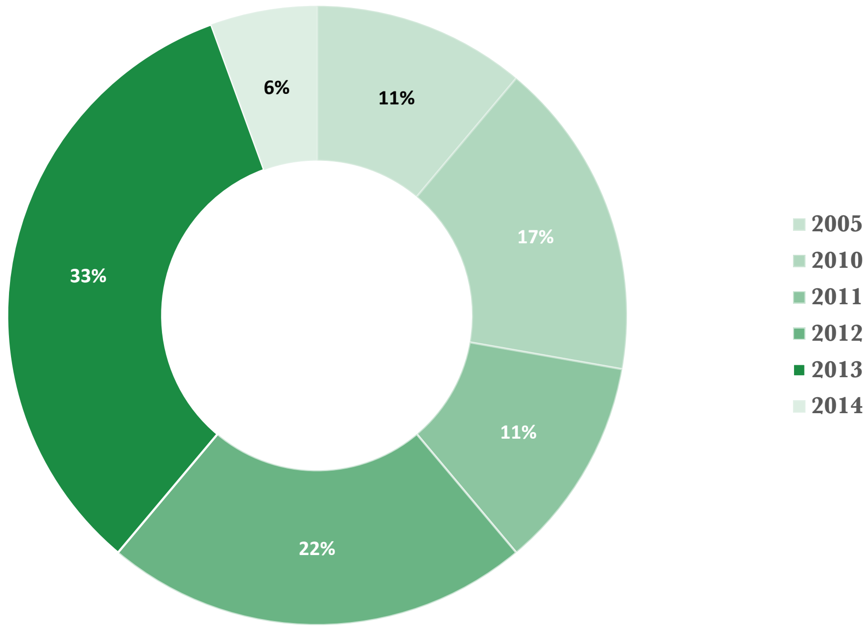

Figure 2

Year project was completed.

BUILDING TYPE

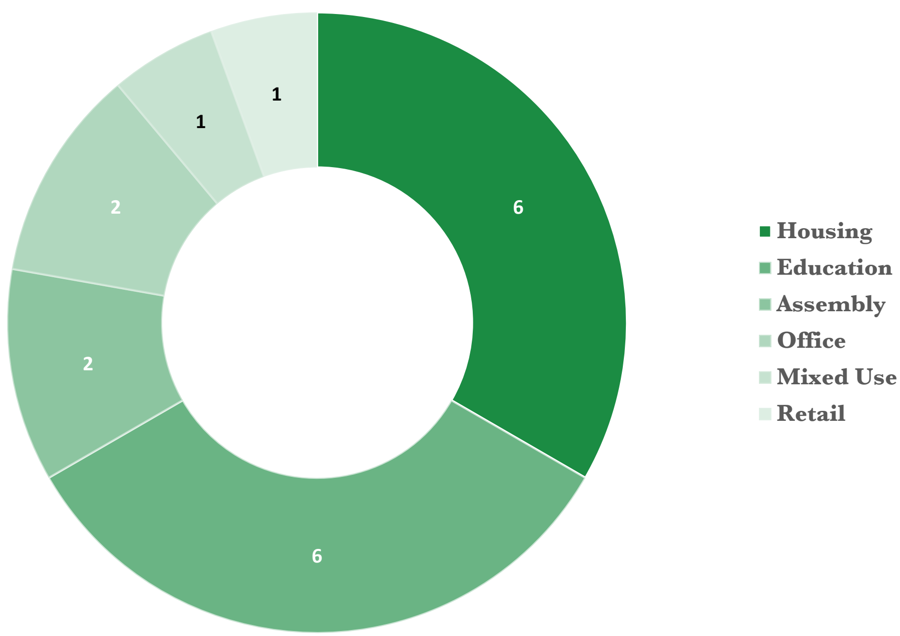

Figure 3

The type of buildings included in this report.

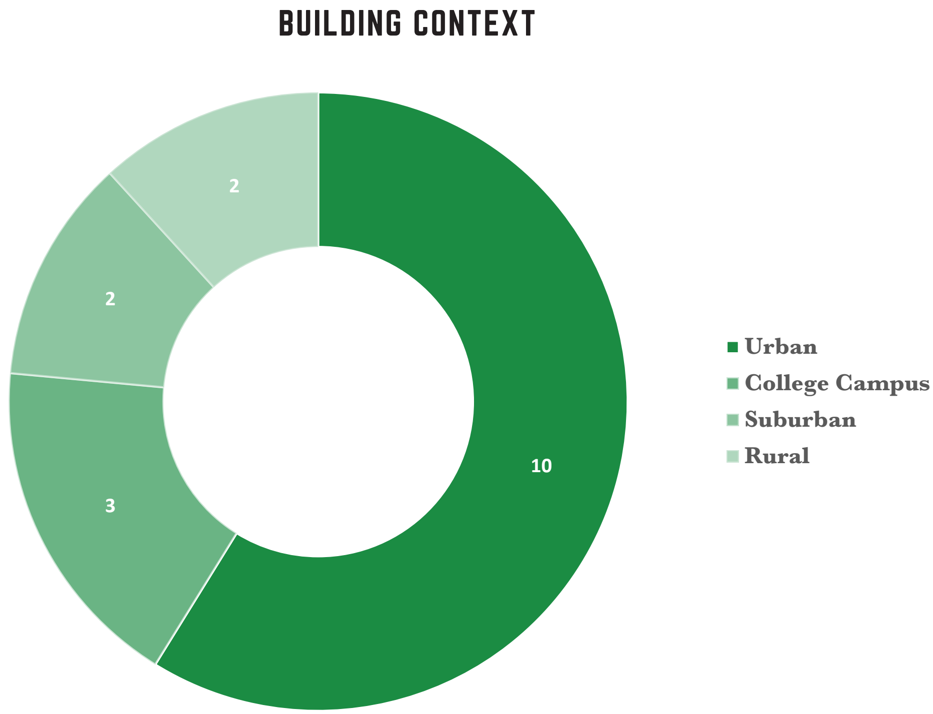

Figure 4

The building context

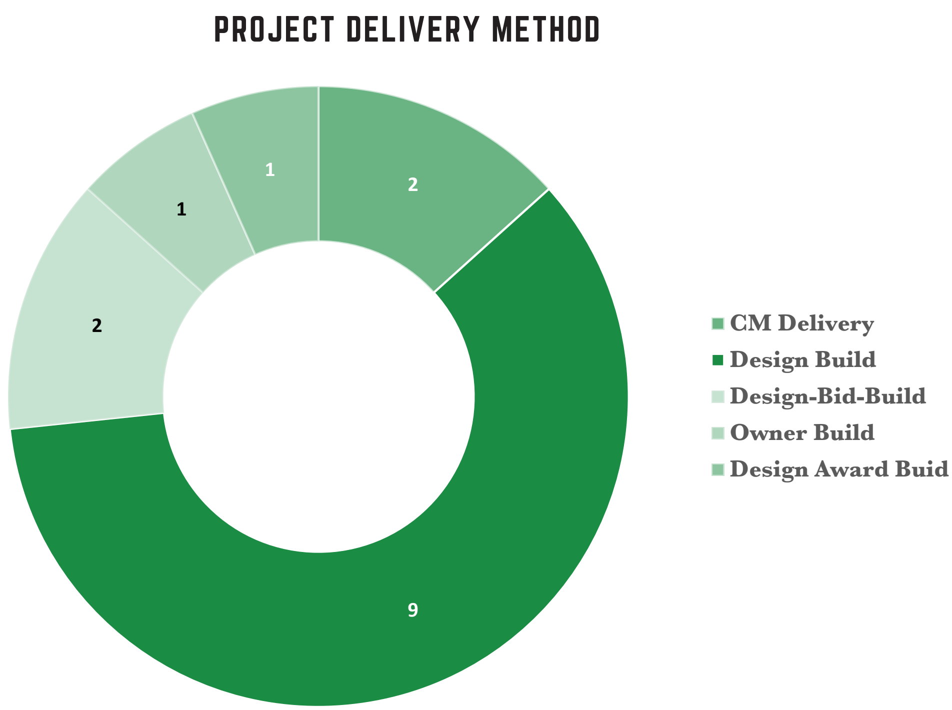

Figure 5

The project delivery method.

SQUARE FOOTAGE

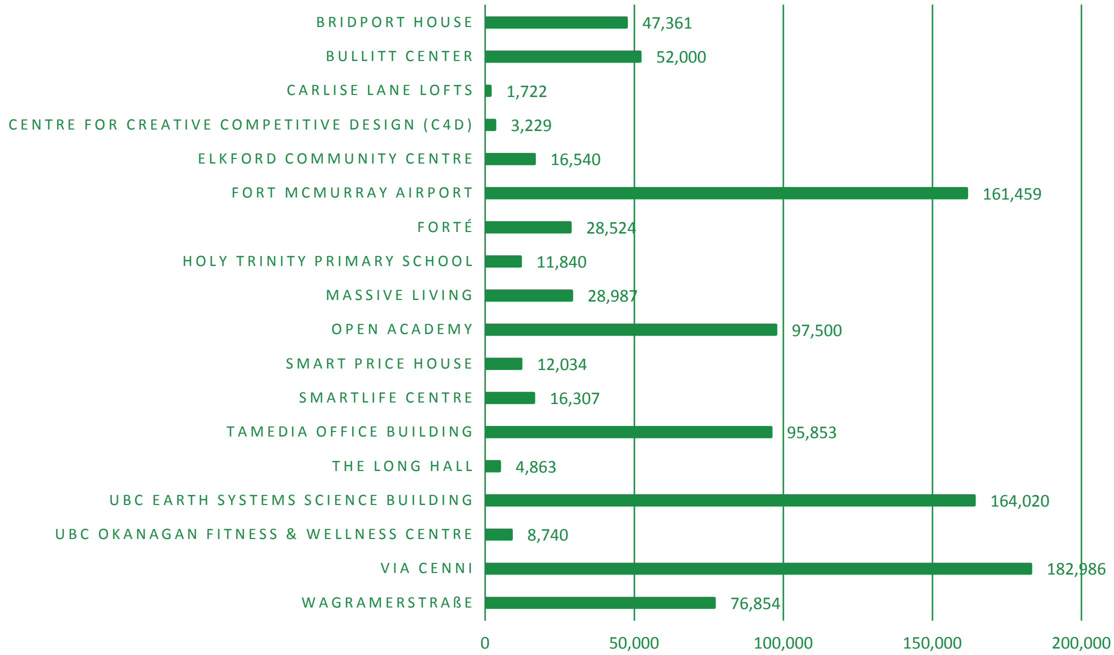

Figure 6

Square footage is measured in Gross Square Feet

BUILDING FOOTPRINT

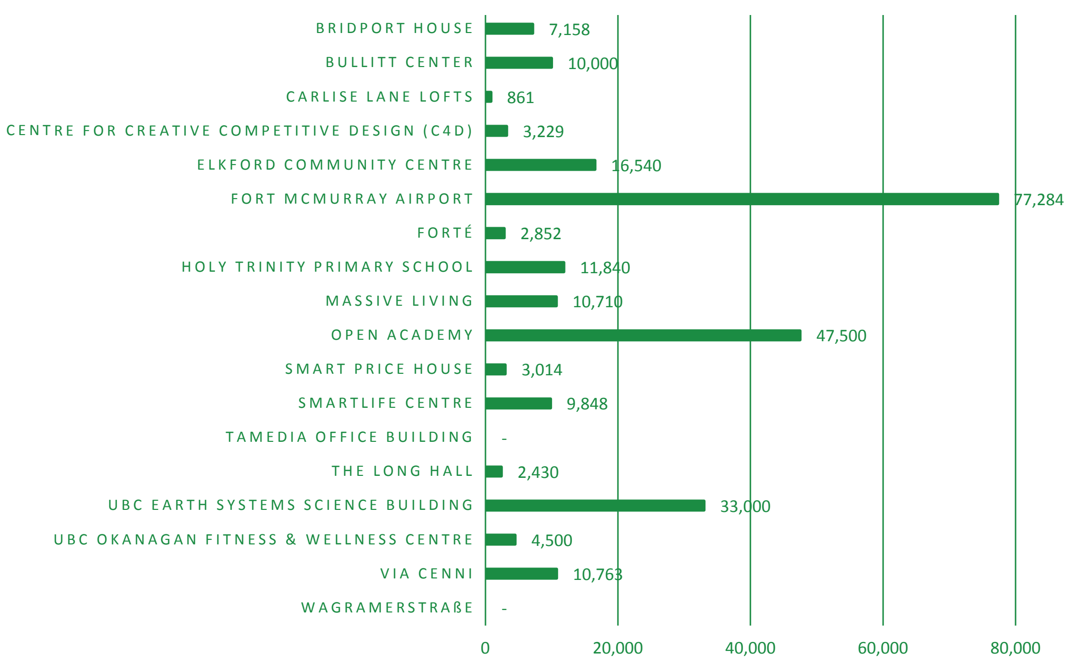

Figure 7

Building Footprint in Gross Square Feet

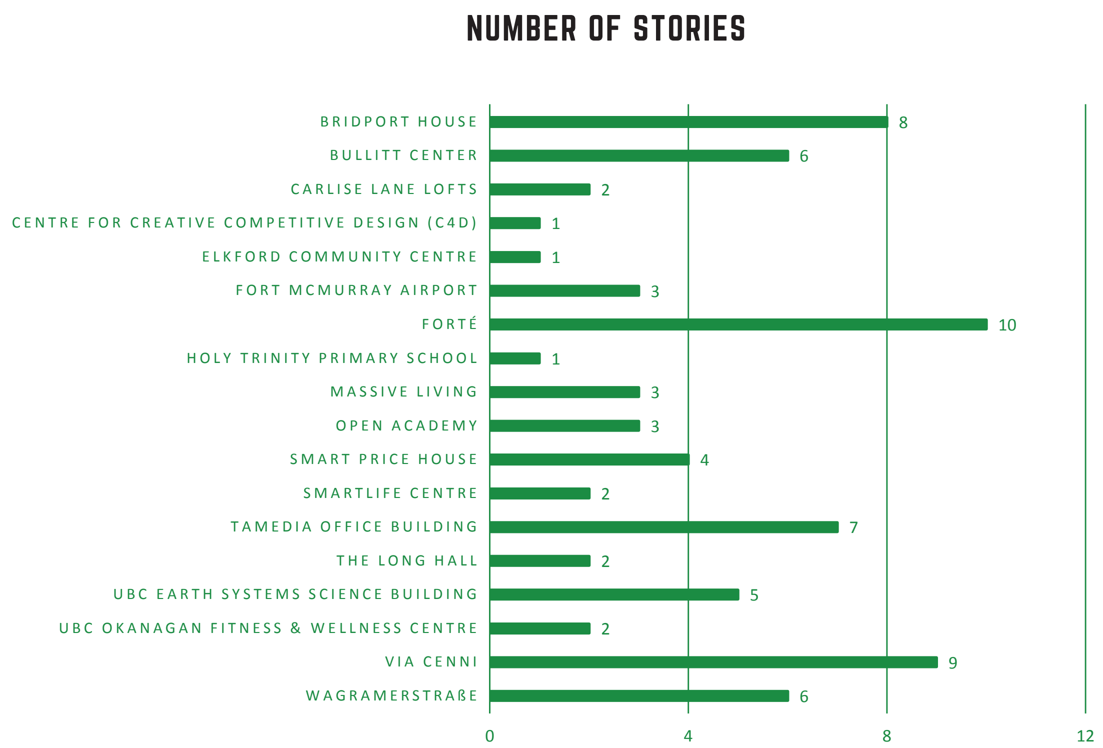

Figure 8

Stories included in this data set are not limited to stories in solid timber construction.

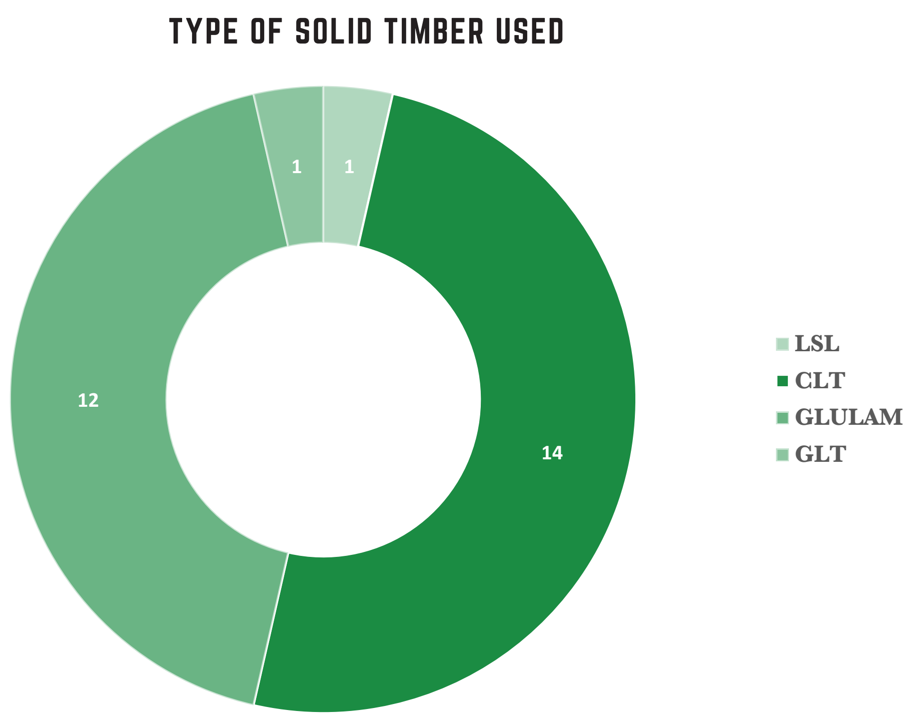

Figure 9

The type of solid timber used

DISTANCE FROM FACTORY

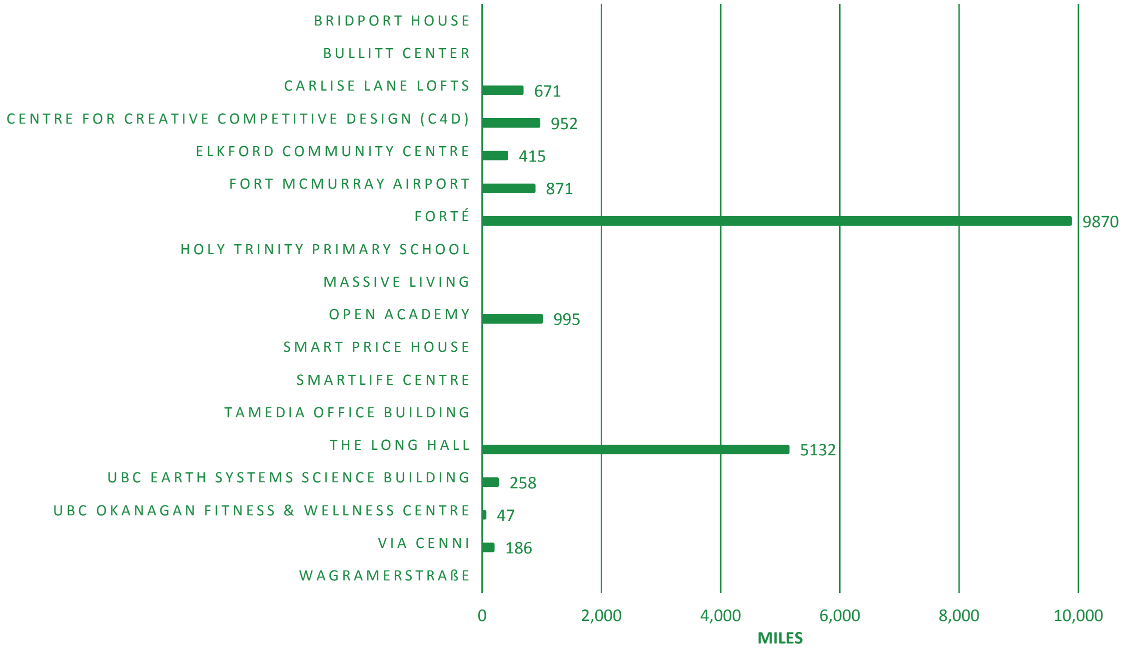

Figure 10

The distance in miles from factory to project location.

SOLID TIMER VOLUME (FT³)

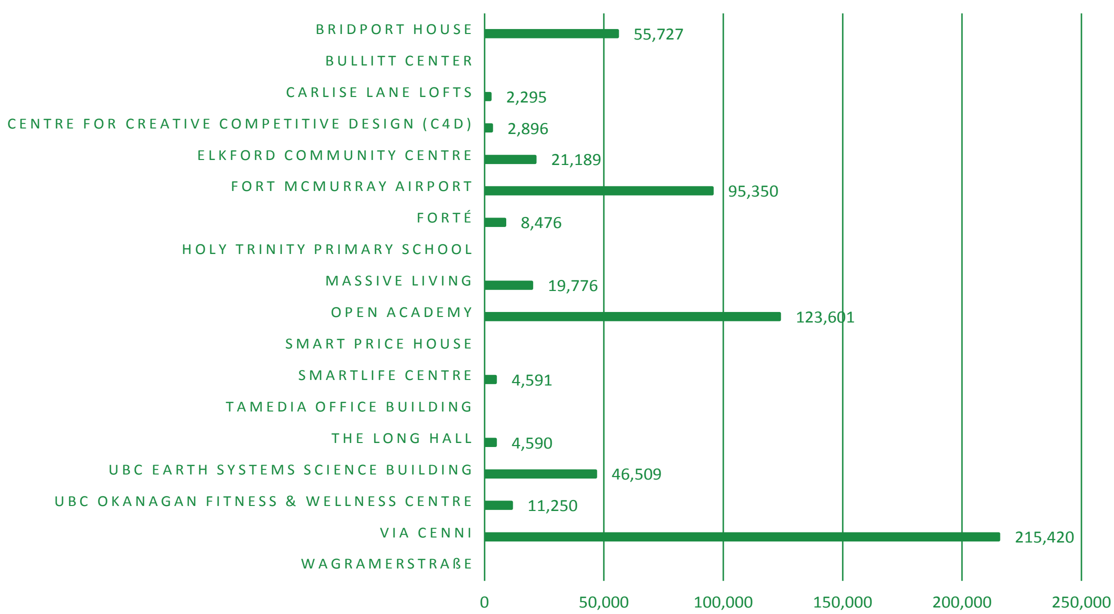

Figure 11

The volume of Solid Timber used in each project.

COST

Questions regarding cost:	Figure #
What was the vertical construction cost?	*13*
What was the design cost?	*14*
What was the solid timber contract cost?	*15*

Cost was difficult to compare to traditionally built projects given the complexity and high level of design each of the case studies required. Even with an average of 4% cost savings over traditional construction, we also found STC to be as expensive if not more so than traditional methods in a few of the case studies (*See Figure 16)*.

Also, 4 of the 7 comparisons were considered 'pilot projects' for STC or were the first solid timber structures designed and constructed by the stakeholders of those projects. Among these projects, there were only two projects that were considerably more expensive to construct than traditional projects. Projects that were not considered 'pilot projects' all came in under cost to their traditional counterparts.

The repetition of doing STC and building upon the knowledge gained from previous projects helps to streamline costs and increase productivity. The evaluation suggests one-off STC projects have a high possibility of being more expensive than traditional construction.

The most important item to note in this cost analysis, is that STC is conducive to greater cost control when compared to traditional on-site construction. This is attributed to the inherent ability to reduce the number of change orders in any given STC project.

In conventional construction delivery, change-orders cause significant cost increases. In a recent study conducted in Montgomery County, Maryland, the Office of Leglislative Oversight studied 17 county government building projects that reached substantial completion in 2009-2013. The study found an 8% overall increase in contract costs due to change orders. (OLO, 2014)

COST PER SQUARE FOOT

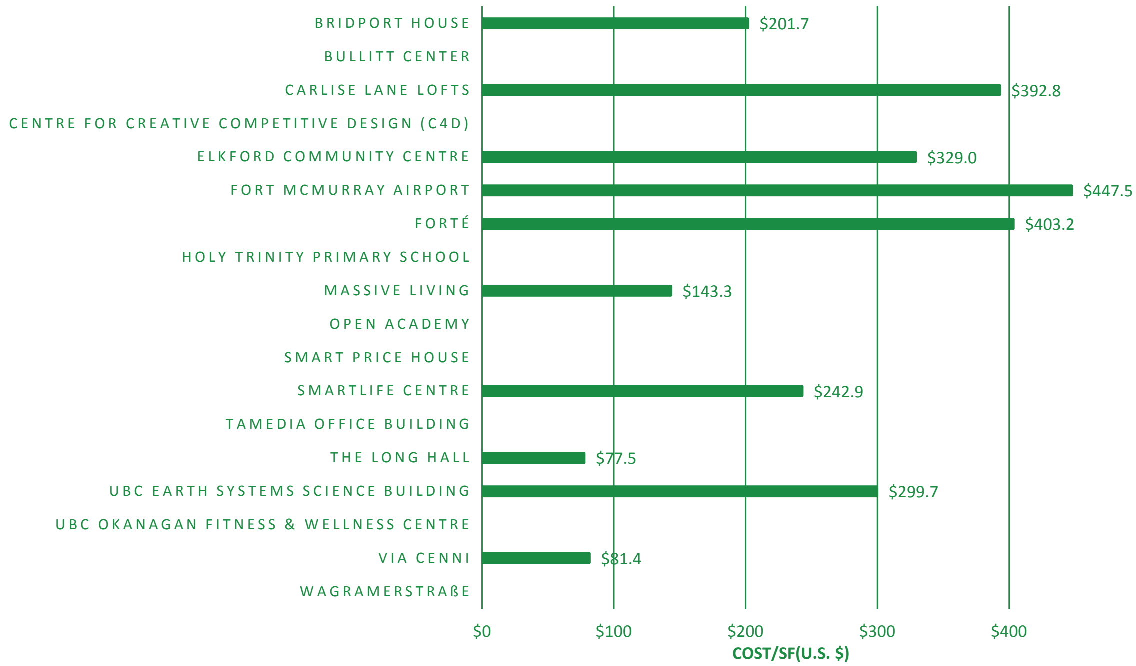

Figure 12

Raw cost per SF at time of construction converted to US Dollars.

VERTICAL CONSTRUCTION COST

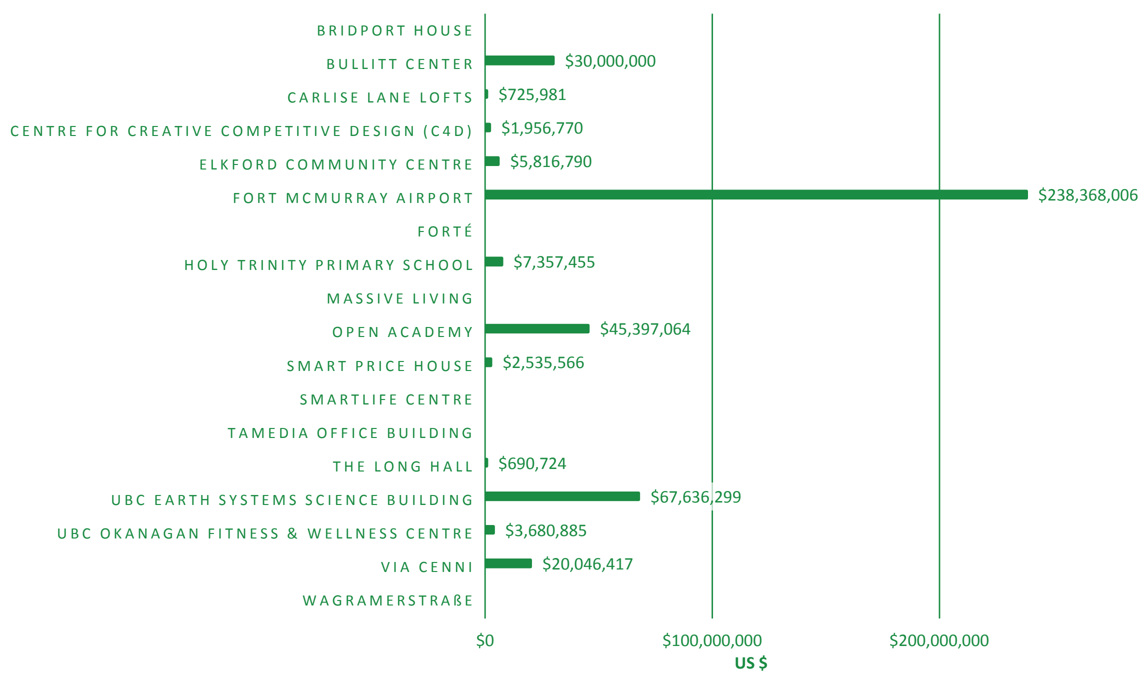

Figure 13

Raw vertical construction cost at time of construction converted to US Dollars.

DESIGN COST

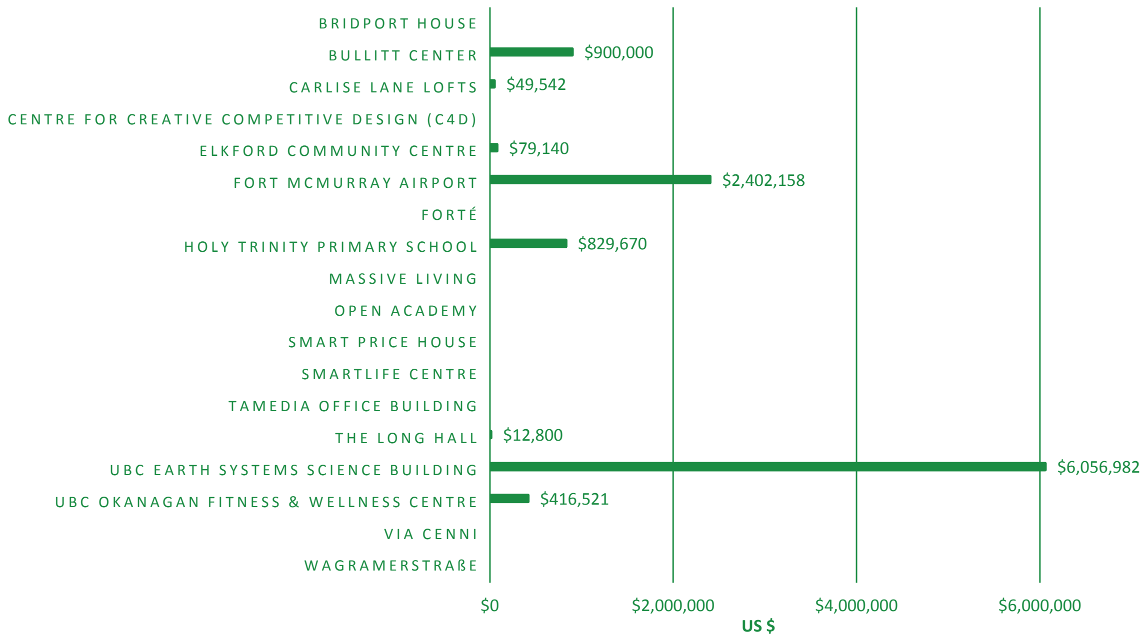

Figure 14

Design cost at time of construction converted to US Dollars.

SOLID TIMBER CONTRACT COST

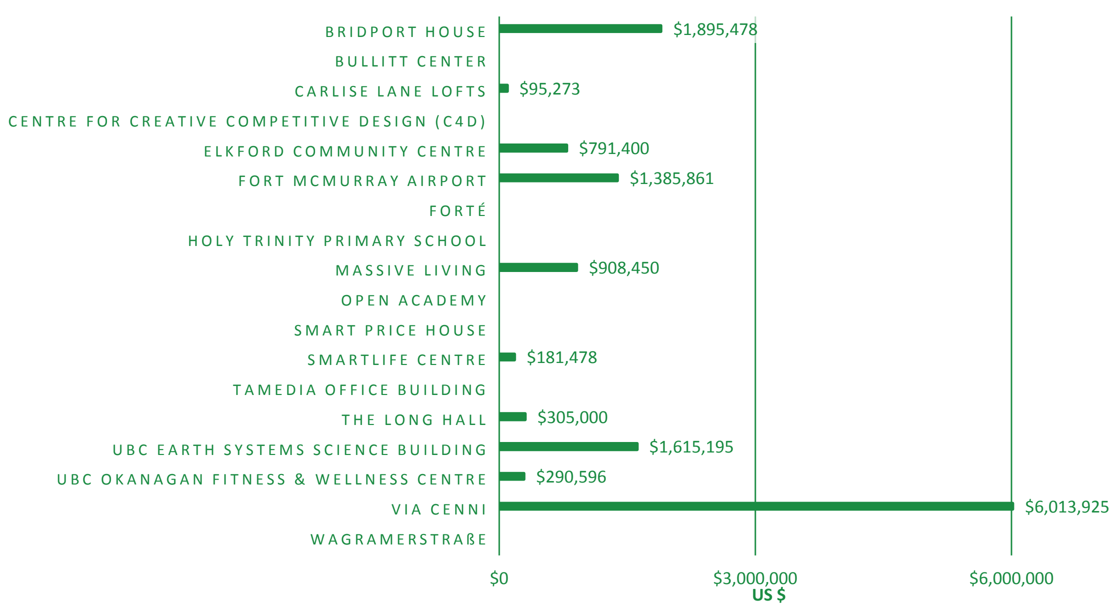

Figure 15

Solid timber contract cost at time of construction converted to US Dollars.

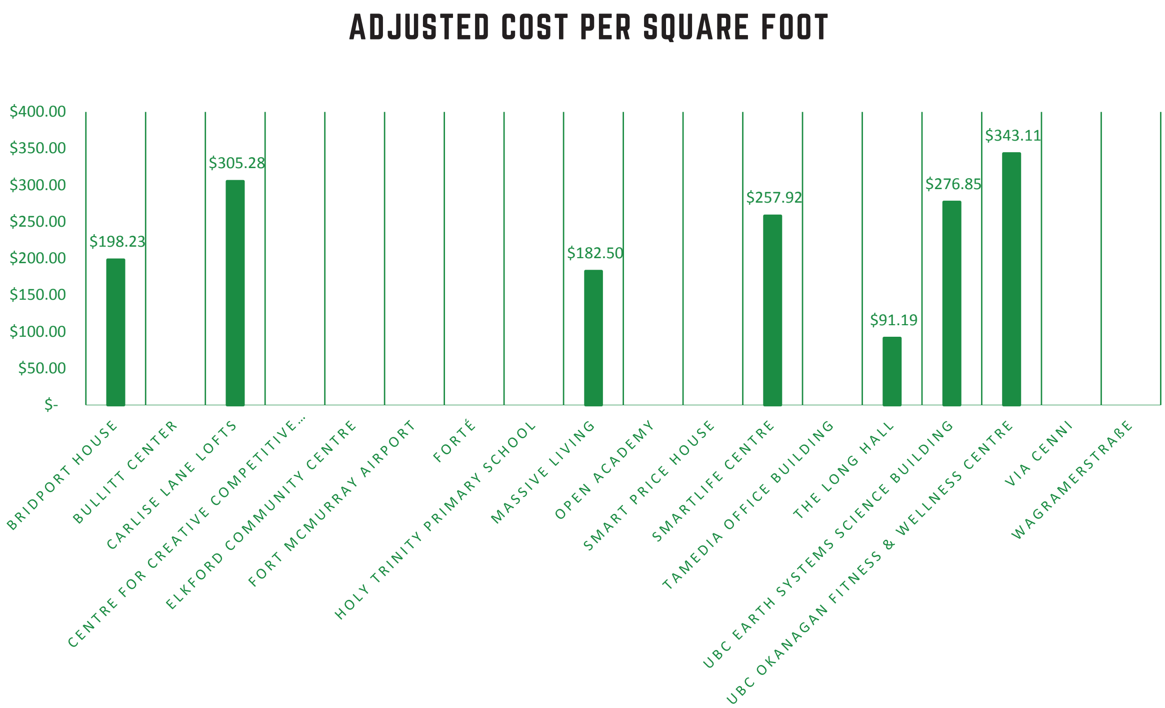

Figure 16

The vertical construction cost per square foot of the 7 chosen STC case studies, Normalized to the first quarter of 2014 in US dollars and Washington D.C.

SCHEDULE

The reduction of time in the production of buildings that use solid timber construction is one of, if not, the greatest incentive that this method of construction has to offer. It is also the majority motivation as to why STC was used in these projects. The following questions involve schedule:

	Figure #
What was the project duration?	*17*
What was the design duration?	*18*
What was the construction duration?	*19*
How much time was the solid timber in the factory?	*20*
How long did it take to erect the solid timber?	*21*

STC shows an average of 20% schedule reduction across the compared case studies. An average of 12.7 months for STC cases and 15.4 months for conventional construction (*See Figure 23)*. Since the solid timber panels are built in a factory, the site-work and foundations can be constructed simultaneously. This reduces the lag time that a traditional on-site built building has where site-work, foundations and building construction occur consecutively.

On average, the solid timber took 2.9 months to fabricate in the factory, and just 60 days to erect on-site. Small amounts of labor are needed to erect solid timber. This is shown in the following case studies below (Lease, 2013):

- Bridport House - 14 weeks to erect with only 4 skilled laborers + 1 supervisor
- Open Academy - 16 weeks to erect with only 8 skilled laborers + 1 supervisor
- Forté - 10 weeks to erect with only 5 skilled laborers + 1 supervisor + 1 trainer

The time saved using STC opens a whole window of opportunity for cost savings. This is substantiated in a Return on Investment study found on pages 42-44 of this report.

In the Office of Legislative Oversight study on the Change Orders in County Government Construction Projects, change orders increased the 17 case studies construction time by 30.3%. In two of the 17 case studies, change orders more than doubled the construction time. (OLO, 2014)

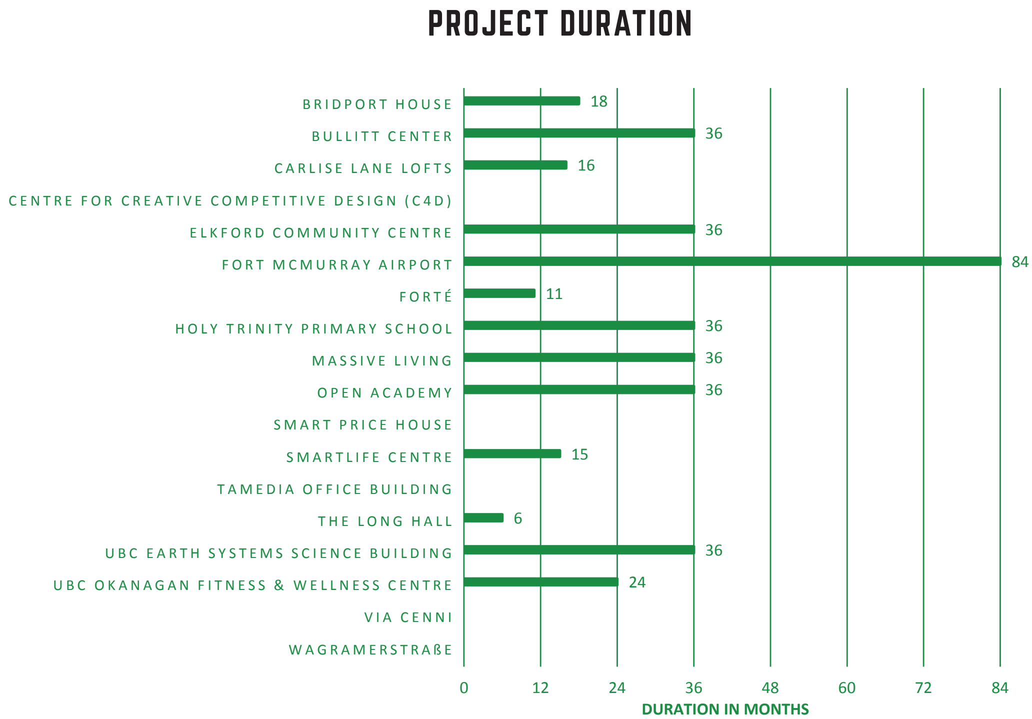

Figure 17

The total project time in months.

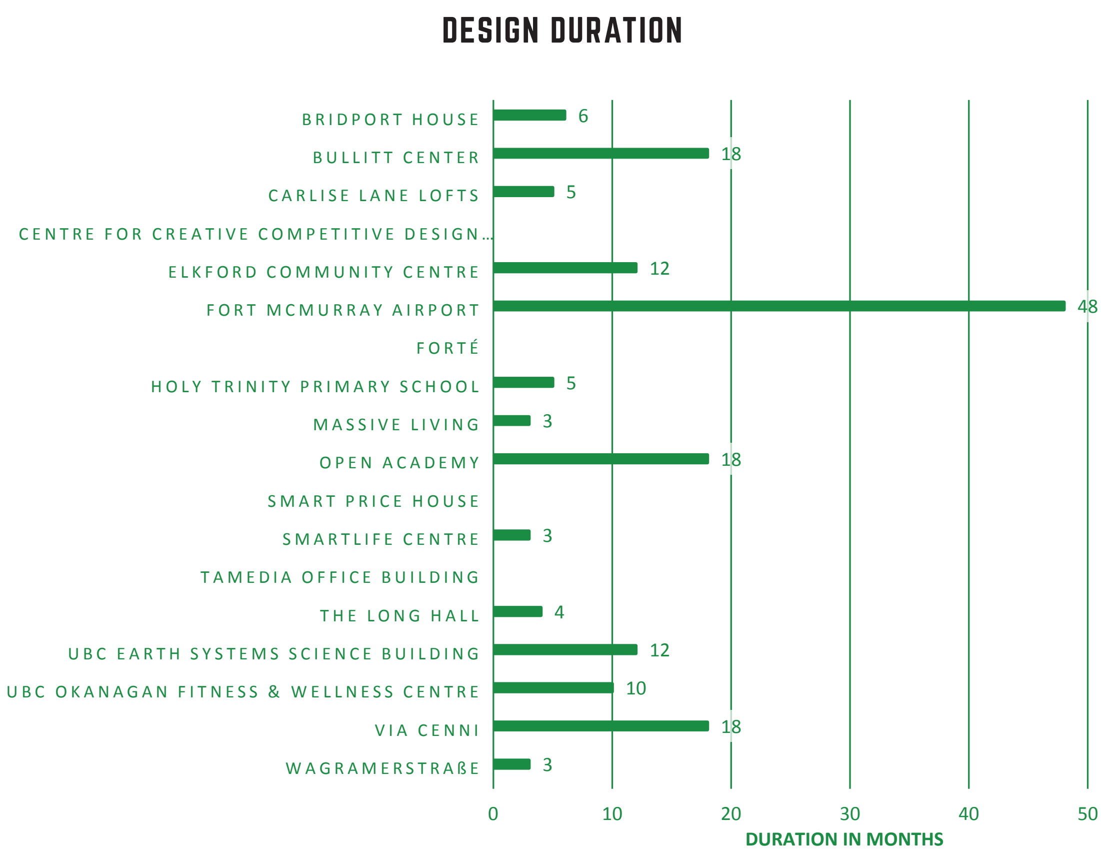

Figure 18

The project design time in months.

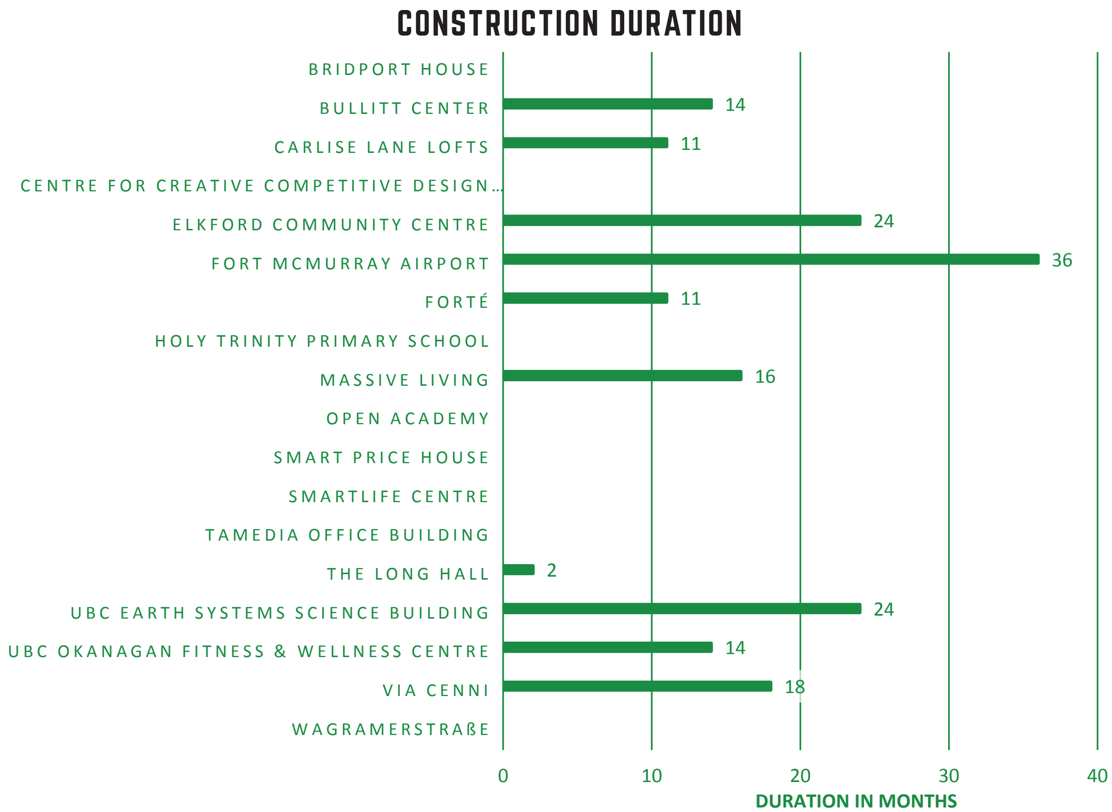

Figure 19

The project build time in months.

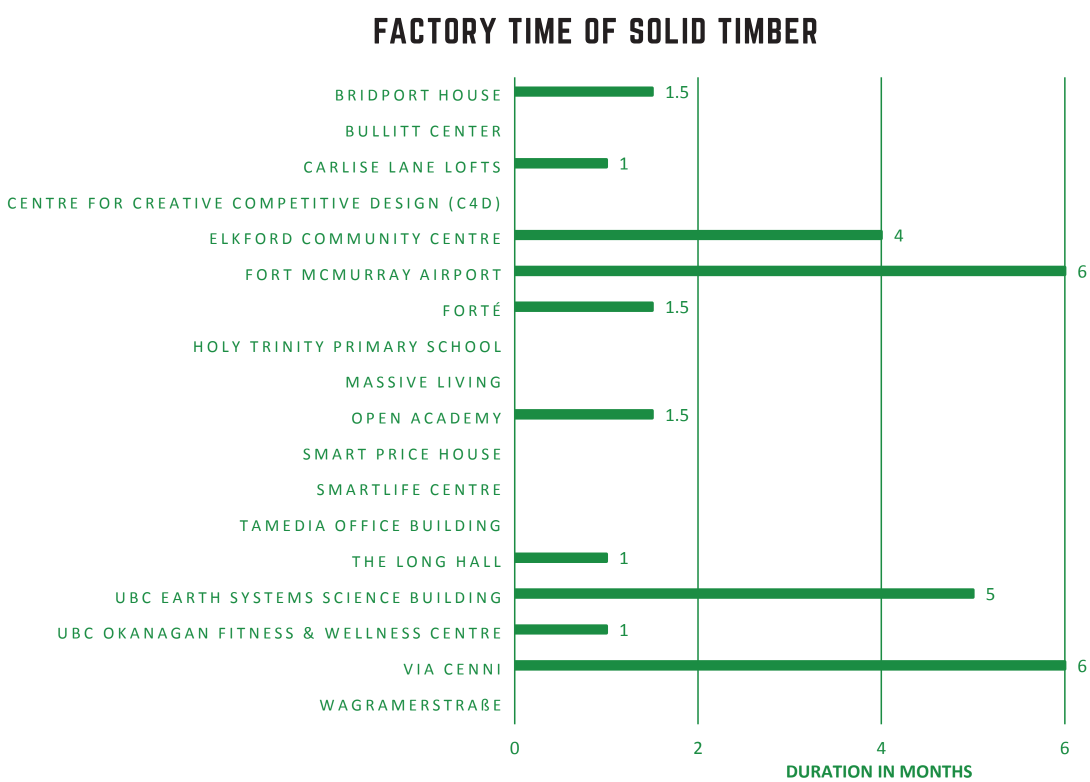

Figure 20

The factory production time of the solid timber in months.

SOLID TIMBER ERECTION TIME

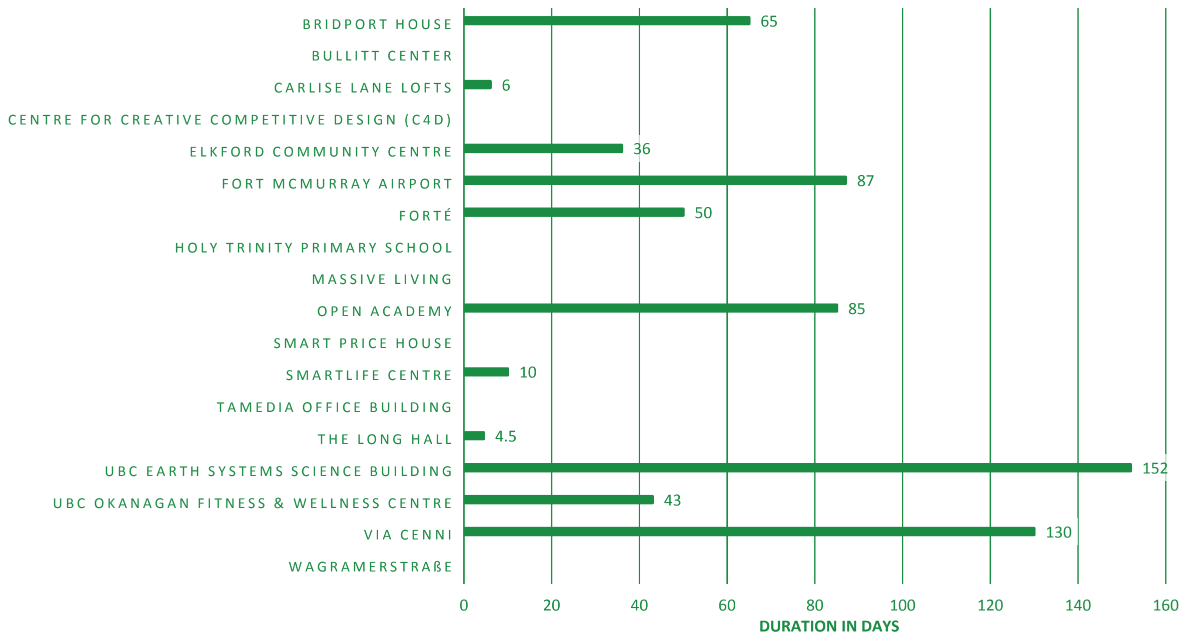

Figure 21

The time in days for the erection of the solid timber.

Forté

Photo Credit: Lend Lease

QUALITY AND SAFETY

This topic includes questions of quality and safety. These topics present overlaps that reinforce the cost and schedule findings:

How many change orders were in the project?

How many reported safety incidents were there?

How many labor hours were there?

Across the 11 case studies that provided an answer to these questions, the number of change orders is averaged to be 3.7.

According to the 11 cases in this report that provided an answer on safety, there were no safety incidents reported. Specifically, in the case of Forté there wasn't a single incident that required a first aid kit. With the quantity of given information, no claim can be made that is statistically significant concerning safety.

Not a single project was able to supply labor-hours productivity data throughout the entire pool of cases. It is uncertain why the construction industry does not track labor hours as a means to establish productivity. Answering this is an important area for further investigation, as it will be necessary to evaluate the relative productivity gains that may be possible with STC methods.

Elkford Community Centre
Photo Credit: Douglas Sollows Architect Inc.

QUALITATIVE

The following qualitative questions were asked to gain a better understanding of how STC performs against conventional construction methods. This information is intended to foster understanding of how STC can be improved. The table on pages 35-36 includes re-occurring themes and answers that surfaced during the phone interviews and online surveys, and gives a summary of the lessons learned.

Why was STC used on this project?

How was the structure of the team unique because of using Solid Timber?

What digital software was used?

Were there any major obstacles that had to be overcome?

What were the greatest successes of the project?

What would you do differently next time?

What were the lessons learned from this project?

WHY WAS SOLID TIMBER CONSTRUCTION CHOSEN?

Interestingly, the choice for using solid timber was made by owners. A few of the projects were from competitions wherein using wood was a requirement. This shows the progressive and innovative drivers from owners demanding timber first initiatives. The specific reasons for wanting to use wood were to reduce the carbon impacts and the aesthetic look and emotional influence of wood generally.

Close behind the design requirements of ownership, speed of construction was the reason for utilizing STC. Multiple factors led to a need for a shorter construction period. These included shortened building seasons and the need to minimize disruption of surrounding structures, among others. A few of the case studies were built in very cold climate zones, and threat of snow and freezing temperatures were a top priority. In other case studies, remote or urban sites that limit access to material suppliers and staging areas limited the use of traditional building methods.

HOW WAS THE STRUCTURE OF THE TEAM UNIQUE?

The primary differences in the structures of the AEC teams was in the hiring of structural engineers that were familiar with STC or specialized timber projects, and often bringing in specialized consultants for assistance in design and construction.

For construction there were a few specialized crews that were hired who were familiar with the technology, or similar building technologies such as tilt up concrete and heavy timber.

WHAT DIGITAL SOFTWARE WAS USED?

The most common software package used by architects was AutoCAD 2D followed by SketchUp and Vectorworks.

A few of the architects have moved to Revit or another BIM program since the completion of the selected case studies.

The primary fabrication software used was Cadwork, followed by hsbCAD.

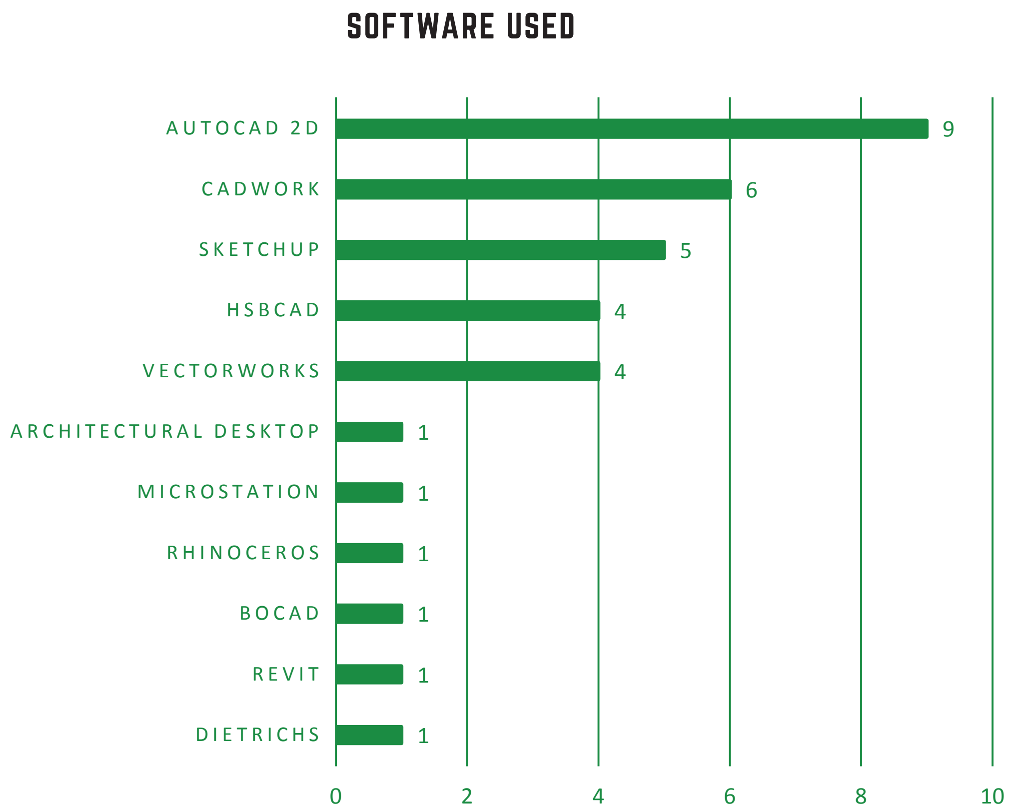

Figure 22

Design and fabrication software used.

WERE THERE ANY MAJOR OBSTACLES?

The greatest obstacle to overcome was getting code approval, especially fire ratings. Since CLT is not in the 2012 IBC code book, it falls under an alternative method provision, which requires extensive fire rating approval. Since the time this survey was conducted CLT has been adopted into the 2015 IBC code book. The next major obstacles were acoustics and connection details. CLT is a rigid product and transfers sound when used in floor situations, or as a barrier between elements that vibrate.

The actual connections of panels were an obstacle that took careful planning, and investigation.

WHAT WERE THE GREATEST SUCCESSES?

Short building time, innovation, and market exposure of STC were the top answers. Quality and aesthetics followed. The speed of construction was one the of main drivers to why solid timber construction was used, and this ultimately became the greatest success of the projects. Innovation and the use of STC were additional drivers that the stakeholders found to be great successes.

Quality of construction and aesthetics were quoted by the stakeholders as great success of the projects. Being able to use wood in general in an innovative way, coupled with using a relatively new wood structure system became great successes.

WHAT WOULD YOU DO DIFFERENTLY NEXT TIME?

Most of the stakeholders said they would not do anything differently, but the next most common response was to better design and integrate Mechanical, Electrical, and Plumbing (MEP) systems. Respondents indicated that designing all of the MEP chases takes a lot of extra time, and some stakeholders mentioned they wished they would have taken more time in design to integrate them further. In addition, better coordination among the project team, use of BIM, and a better understanding of the logistics involved with STC was mentioned.

WHAT WERE THE LESSONS LEARNED?

ADVANTAGES

Speed

One project was erected in as little as 4.5 days. In addition, multi-story structures can begin subcontractor work once the first story is erected (i.e electrical, mechanical, etc..) This cannot be done as efficiently in steel or concrete.

- Bridport House reduced schedule by 8 weeks compared to traditional methods. (Group, 2011)
- Forté reduced schedule by 3 months compared to traditional methods. (Will, 2014)

Weather Versatility

Due to the "dry process" of STC buildings, they can be assembled during any season. Most CLT is sealed and is unaffected by snow, or water during construction.

Raw Material

A majority of solid timber comes fully finished, with the ability to be exposed as a interior surface. This can also cut back on finishing materials (gyp board, paint, etc.), as well as provide an innovative use of wood.

Carbon Reduction

Wood is a carbon sequestering material, and it greatly minimizes the carbon footprint for each project.

Remote Sites

Panels are fabricated off-site, and then shipped or trucked to the site. Once arrived on-site they can be assembled very quickly. This method is especially helpful in rural locations, or locations with a minimal labor force.

DISADVANTAGES

Knowledge & Labor

Solid Timber is a very different form of construction, when compared with stick framing, concrete, or steel. Majority of general contractors, designers, and engineers are not familiar with solid timber and how it is constructed. A majority of the time a consultant was hired, or a structural engineer that was familiar with the technology was procured for design assist. Special construction crews were recruited to assemble the system.

Research

Due to the lack of experience and projects completed in North America with STC there is still a lack of information on construction methods, connections, and delivery methods.

Logistics

Most panels are shipped either on a truck or in a container, and each method has its own transporting capacity. Shipments must be shipped to the site in order from foundation to vertical termination, placing the first piece to be erected on top of the shipment. Re-arranging panels and temporarily storing them is costly and wastes time.

Planning

Due to the finished nature of CLT panels mechanical, and electrical systems are located before fabrication. Knowing where and how these chases will effect finishes and design is crucial.

Designing for STC is a completely different process. All design work must be front loaded and completed before information is sent to fabrication. The scheduling of this process is then front-loaded, compared to traditional construction.

Labor Costs

With manufacturing taking place in a factory there is no need for as much on-site labor/man hours, as well as site preparations, etc.

Weight

Foundations can be smaller, and buildings can be built taller for the similar costs as traditional methods of construction. This light-weight structure can also help in special site conditions such as near waterfronts and where soils may not be as favorable.

- Using CLT for the Bridport House made it possible to double the replacement structure with only a 10% increase in overall weight (Products 2012)

Precision

With tolerances within millimeters the connections and envelope are tight. This also increases energy efficiency.

Safety

Given the finished nature of the panels there is less potential for injury. There are fewer parts to assemble and transport. For example, Forté, a 9 story structure did not have one first aid incident during construction

Acoustics & Vibration

Due to the rigid nature of the panels this construction is susceptible to sound and vibration that can be transferred through walls and floors. Extra sound proofing is usually needed to mitigate that sound.

Job Displacement

Less man power and labor hours are required for STC and so this decreases the amount of jobs that on-site construction currently provides.

Code & Permits

Given that STC is relatively new in North America, a lot of building officials are not familiar with structural, fire, and acoustics of the panels. This often requires more documentation, engineering, and longer time frames to get permits.

Wind

Wind is a concern when craning CLT panels from the truck to the site. Given their wide surface area they are greatly affected by high winds. Construction can be halted to wait for weather conditions to improve.

Component Flexibility

The massive panels are too heavy to handle by hand, thus requiring heavy machinery and cranes to install. This limits the amount of on-site adjusting that can be done.

BEST PRACTICES

- **Design to the product** - Standard CLT panels come in set dimensions for each panel. For example, some start at 10' x 40' up to 90' long. Walls, floors, and roofs should be designed to maximize the yield of the standard dimensions the fabricator uses. Designers need to be educated on fabrication machine capabilities, methods, and limits.

- **Complete the design** - It is difficult to make changes to a solid panel on site, given the "finished" nature of the product. The location of electrical chases and penetrations in the panel need to be designed before fabrication. This means all of the designs and drawings need to be complete before they are sent to fabrication. This front loads the design process, but quickly speeds up construction.

- **Start small and scale up** - A large number of the case studies surveyed were pilot projects or were using solid timber in an innovative way for the first time. (Forté, UBC Earth Systems, The Long Hall, and Elkford Commnity Centre). Using the project as a testing ground, some stakeholders then took that knowledge gained and created additional projects.

- **Talk to local Authority Having Jurisdiction (AHJ) early** - AHJ's need to know early on in the design process the plan to build using solid timber. Additional documentation/approval may be needed. This can also help to expedite inspections and permit approval.

- **Design in 3D/BIM** - Designing in a 3D software provides clash detection and identifies possible problems before fabrication. This also speeds up the process for fabrication and providing a single model to all subcontractors increases consistency.

- **Not all trades are as accurate as CNC machinery** - For example, some trades only come within ½" to a ¼" inch tolerances, while CNC machines have tolerances within millimeters. Connections between CNC cut panels and on-site fabricated materials can become complicated with different tolerances. Allow room for proper tolerances in design and fabrication.

- **Finish of the Timber** - There are different types and grades of solid timber panels, and some even come with certain sealers or finishes from the fabricator. Understanding how panels will be exposed is critical in the design process.

- **Collaborate Early** - All stakeholders in the project (owner, architect, fabricator, manufacturer, GC, etc.) should be working together from the beginning. This collaboration can help speed up the project schedule considerably, and help to avoid mistakes.

  It is very beneficial to bring the fabricator in early to help with design, scope, and limitation of materials on the project. They can also assist the architect in designs and terminology of solid timber.

- **Logistics** - Transportation of panels can require additional permits & even weight requirements depending on the travel route. Evaluate the restrictions of shipping containers/trucks that will be enforced along the transportation route from the fabricator to the job-site. Also, shipping wood panels from state to state may not be allowed due to possible invasive species or bringing foreign material into that state.

- **Software Interoperability** - Coordination with fabricators prior to design about the applications they use to fabricate solid timber. As such, architects should design to communicate with fabricator software as seamlessly as possible. Some of the most common export extensions are .SAT & .IFC.

CONCLUSION

There is a market for STC, and from the project study the most efficient building types are housing, commercial/retail, or office spaces that are 3-4 stories tall or taller.

In addition, markets that can benefit from fast construction times, where owners can start collecting rental/lease income sooner. STC also lends itself lends itself to panelized and repetitive construction.

Massive Living
Photo Credit: Jorj Konstantinov

Holy Trinity Primary School
Photo Credit: Architype

COMPARATIVE ANALYSIS

The following is a summary of the analysis in cost and schedule metrics.

Substantial information to conduct a cost and schedule comparison analysis was provided for 7 case studies.

The results shown in *Figure 23* displays an average schedule reduction of 20%. An average of a 4.2% reduction in cost is proved by using STC rather than conventional methods of construction (*See Figure 24).*

The Open Academy
Photo Credit: Hufton + Crow Photography

SCHEDULE COMPARISON

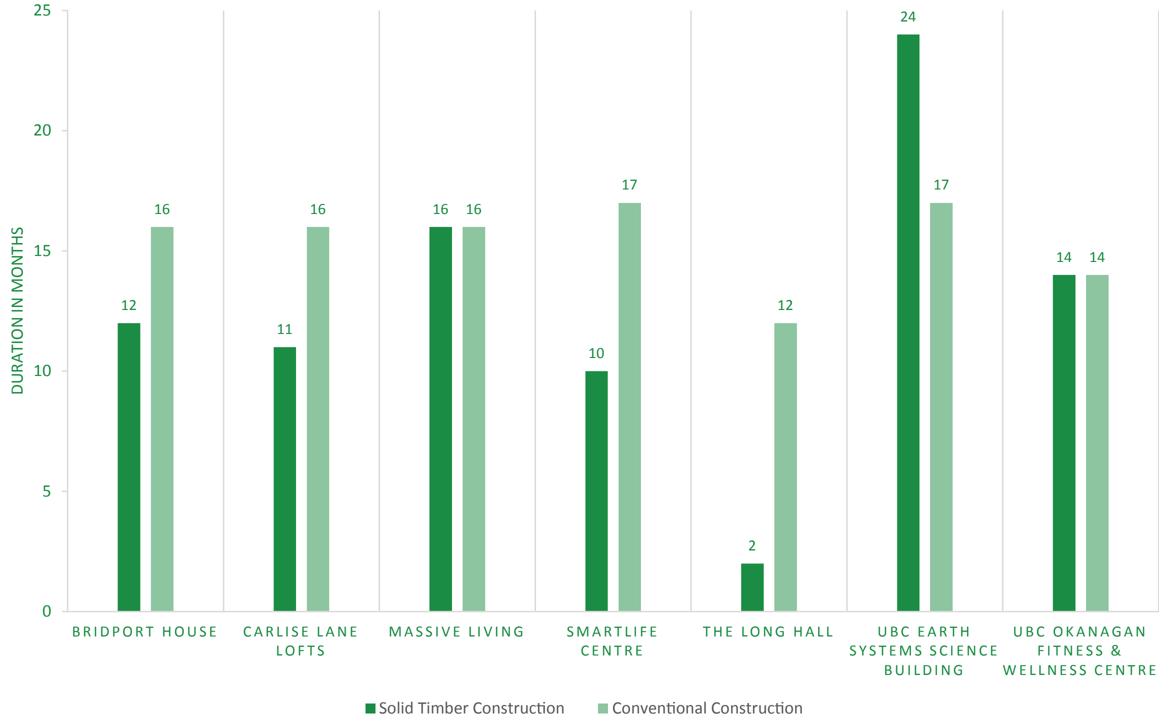

Figure 23

Schedule comparison in months analysed by Cumming Corp.

COST PER SQUARE FOOT COMPARISON

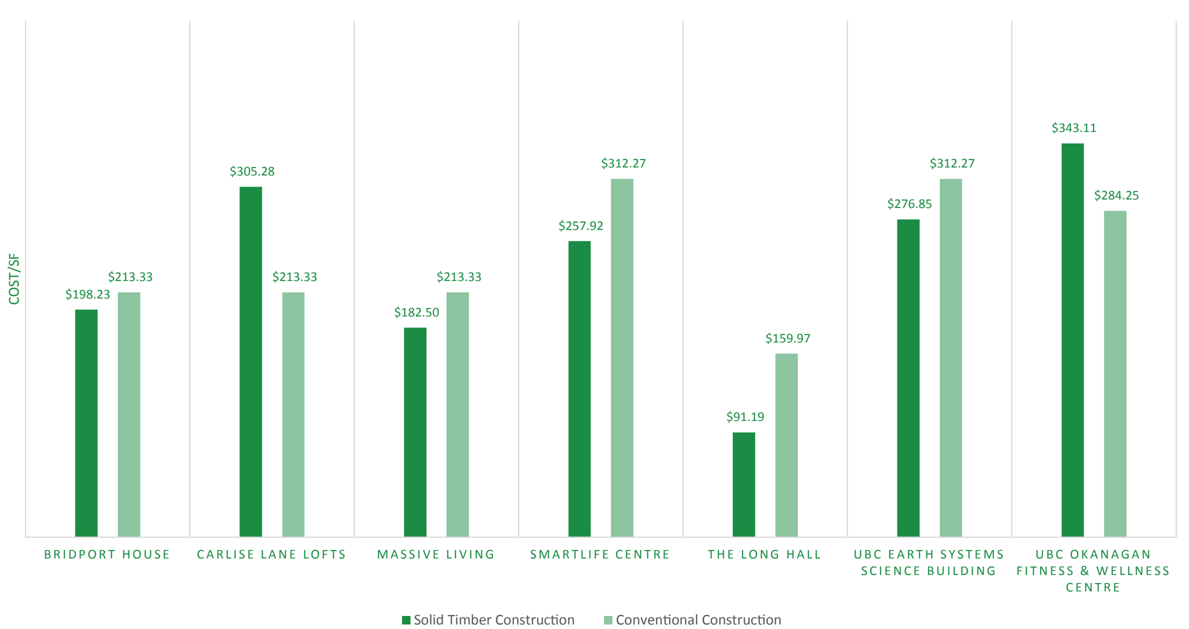

Figure 24

Cost per square-foot comparison analysed by Cumming Corp.

RETURN ON INVESTMENT STUDY

SUMMARY

The pro-forma comparisons show two areas where there is an opportunity to save in cost using solid timber construction. These areas include the cost of the construction loan and the money generated during the time saved. This clearly shows that, though treated individually in the survey results, cost-savings and profitability are tied directly to schedule in most cases.

In the retail space case study at a 25% schedule reduction, $5,187 was saved in construction interest, and $29,333 generated in rental income producing an Effective Gross Income of $34,520. At 50% schedule reduction, $10,350 was saved in construction loan interest, and $58,666 generated in rental income for an Effective Gross Income of $69,017. See *Figure 25.*

The office space pro-forma shows a construction interest savings of $52,214 and a generated rental income of $292,333 for an Effective Gross Income of $345,547 at 25% schedule reduction. At 50% schedule reduction, the Effective Gross Income shows $518,147. See *Figure 26*.

In the charter school case study, $29,821 was saved in construction interest with a 25% schedule reduction. $134,029 was generated in rental income for an Effective Gross Income of $163,851. There would be a construction interest savings of $74,244 with a 50% schedule reduction. A generated rental income of $335,074 for an Effective Gross Income of $409,318. See *Figure 27.*

All three case study pro-formas show an average of $5.81 per square foot in total cost reduction at 25% schedule savings. At 50% schedule reduction, the average cost per square foot savings shows $10.93. At a 25% schedule reduction, the retail, office, and charter school show a cost per square foot savings of $4.32, $8.64, and $4.48 respectively. At 50%, $8.63, $12.95, and $11.20 is saved in the same order.

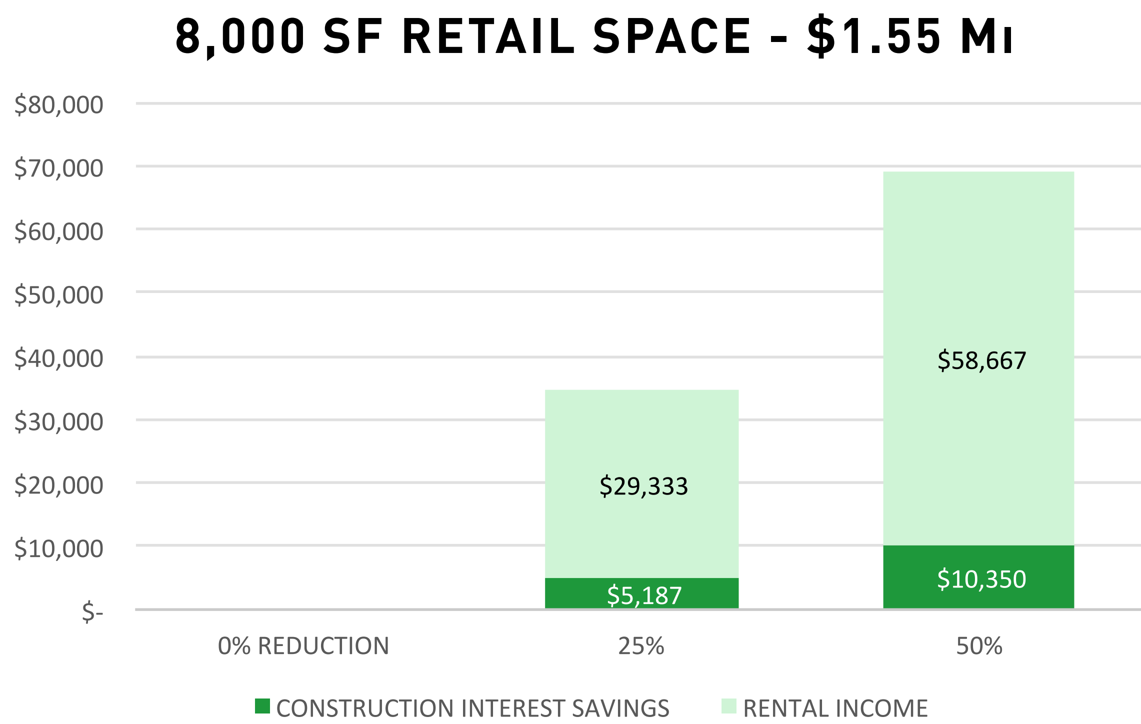

Figure 25

Pro-Formas include a cost reduction in terms of a 25% and 50% faster build time. The lease rate information assumes a 100% building occupancy to reflect the possible savings.

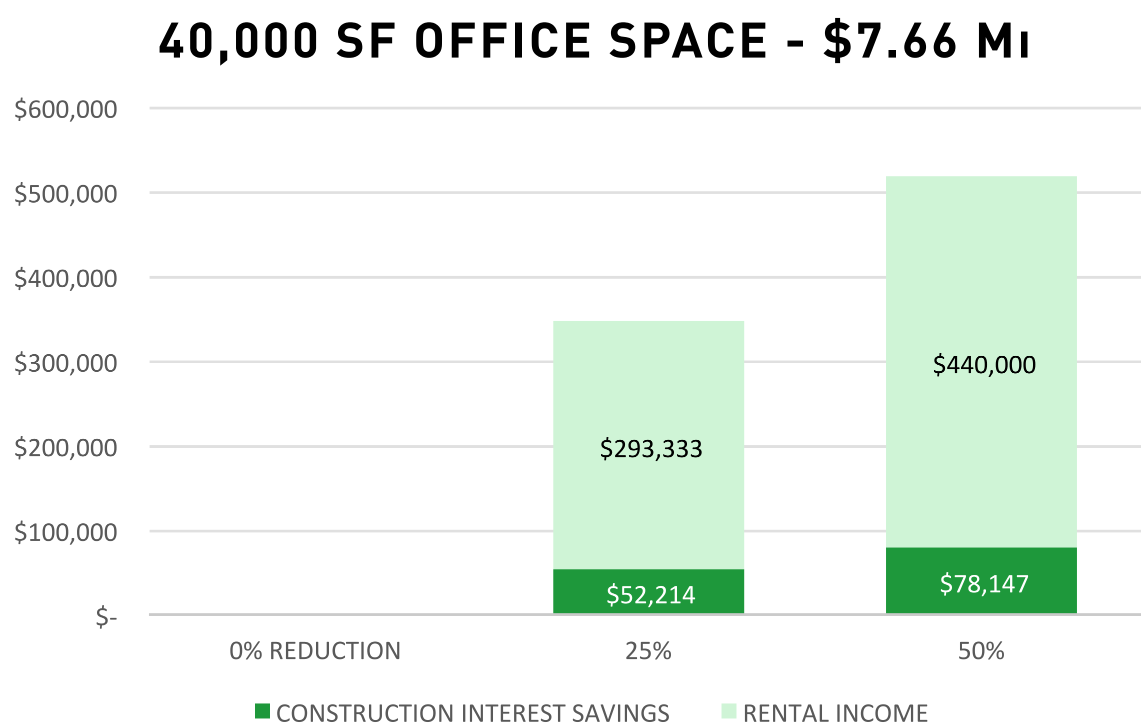

Figure 26

Pro-Formas include a cost reduction in terms of a 25% and 50% faster build time. The lease rate information assumes a 100% building occupancy to reflect the possible savings.

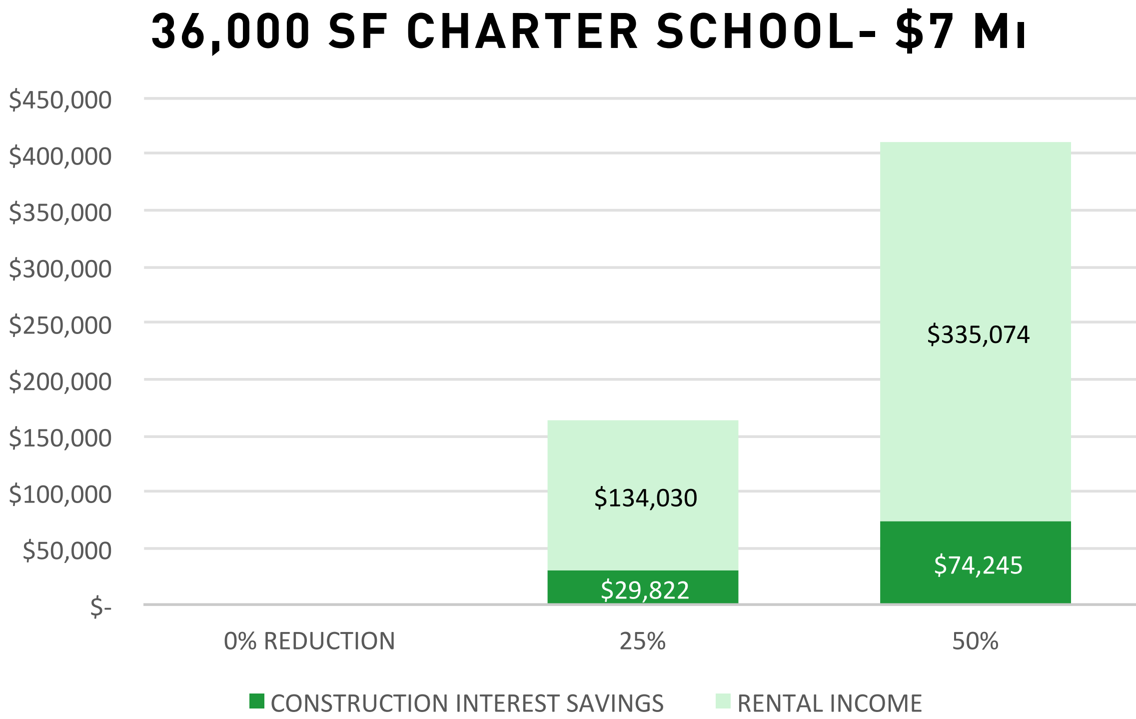

Figure 27

Pro-Formas include a cost reduction in terms of a 25% and 50% faster build time. The lease rate information assumes a 100% building occupancy to reflect the possible savings.

CONCLUSION

SUMMARY

The results from this study indicate:

Quantitative Analysis

Cost	• 4% Savings
Schedule	• 20% Savings
Quality	• 3.7 Average Change Orders
Safety	• 0 Reported Safety Incidents

Qualitative Analysis

Why Chosen	• Speed of Construction • Preferred using wood • Sustainability
Software	• AutoCAD: 26% • Cadwork: 17% • Sketchup: 15% • Other: 42%
Challenges	• Code Approval • Acoustics & Connections
Successes	• Short Build Time • Innovation • CLT Exposure

Lessons Learned

ADVANTAGES	DISADVANTAGES
• Speed	• Knowledge & Labor
• Weather Versatility	• Research
• Raw Material	• Logistics
• Carbon Reduction	• Planning
• Remote Locations	• Acoustics & Vibration
• Labor Costs	• Job Displacement
• Weight	• Code & Permits
• Precision	• Wind
• Safety	• Component Flexibility

Return on Investment

25% Schedule Reduction	$5.81/SF Average Savings
50% Schedule Reduction	$10.93/SF Average Savings

Prefabrication is on the rise. Since the economic downturn of 2008, demand of construction and the skilled labor supply for that construction followed suit. Yet, the skilled labor supply has increased at a lesser rate and has shown to level off, while the demand is still increasing. This presents a gap where STC can take advantage due to its lower labor requirements (*See Figure 28*).

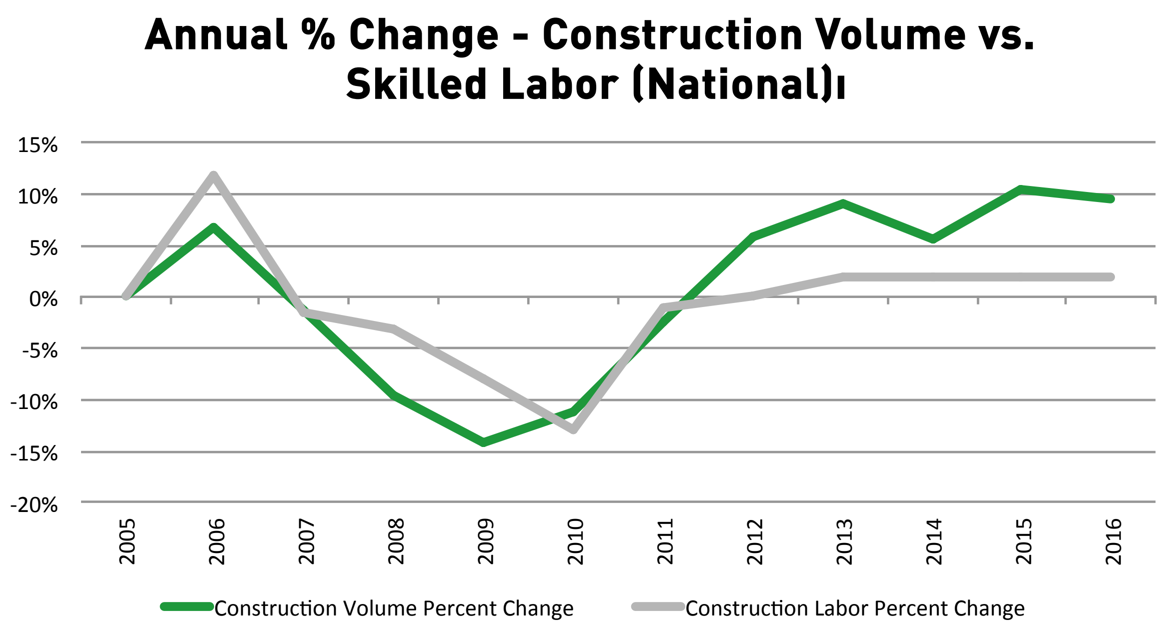

Figure 28

Construction volume vs skilled labor and its forecast showing a gap. (Courtesy of Cumming Corp)

ALTERNATIVE METHODS

This study is limited by sample size, lack of company participation, and the challenge of locating appropriate traditional construction comparisons. However, the findings herein suggest helpful metrics to be developed by projects in the future to demonstrate the value of solid timber beyond initial reductions to cost and schedule. Although effective as a baseline report, construction performance metrics of cost and schedule do not take into consideration the life-cycle benefits of solid timber. This section discusses next steps in this continuum to demonstrate the performance of STC. Suggestions for methods to conduct this future work are included herein.

The study took STC projects and gathered quantitative and qualitative data for each case through literature sources and questionnaires of project stakeholders. This was followed by qualitative interviews of the architect, contractor and solid timber fabricator. The data collected was compared to benchmark case studies by Cumming Corp., a cost estimation consultant. The benchmark projects were traditional site built projects completed in the last 10 years. Although cost data was normalized so the location factor was similar, it was challenging to find projects that were comparable enough to STC cases to draw feasible claims that demonstrate the performance of STC.

Identifying a traditional site built project of similar size in overall square footage, height and number of stories, with similar specification is difficult. Peer review of this study suggests that future studies use two suggested comparative methods to determine cost performance. See *Table 7.*

TABLE 7 - ALTERNATIVE METHODS

Two other methods to compare STC projects to conventional.

Method A	1. Locate a built project whose type is appropriate for STC. This may include multi-family housing, student dormitory, education, retail, or other. 2. Procure the building's as-built drawings and specifications from the project stakeholder team and their permission to evaluate the project. 3. Obtain three separate bids and construction schedules from solid timber builders and partnering general contractors for the project in the same locale as the site built work including all vertical construction costs. 4. Compare the actual traditional site built project to the bid project data for construction performance.
Method B	1. Locate two similar buildings that are going to be built in the near term. Ensure that the buildings are appropriate for STC including multifamily housing, office complex, corporate retailer, or a hotel chain that is building the same brand in two different cities 2. Convince the building owners to build one in traditional stick built construction and the other in STC. 3. Document the construction performance data of cost, schedule, safety, labor hours, change orders, defects, and incidents of injury. 4. Interview the project stakeholders including owner, architect and contractor on each project to gather qualitative data. 5. Compare the site built to STC project across the construction performance parameters and determine what contextual qualitative factors from the interviews lead to successfully STC delivery.

METRIC STANDARDS

In addition to discovering alterative methods that may be more effective in determining performance of STC, the study has also determined key metrics that should be followed in collecting data. This study collected quantitative data and comparative data based on the standards below. In future studies, the STC evaluation effort should continue to refer to sources that establish standards for quantitative data in construction including:

- ASTM
- ISO
- NIST

These standards suggest informational categories of: cost, schedule, incidents of injury, defects, and change orders, that were collected in this report. One data area that was not adequately collected in the 18 STC case studies evaluated was labor hours. It rendered this metric area not comparable. This metric alone could allow traditional stick built work to be compared to STC work for productivity. However, the traditional site built sector does not seemingly collect this data well either. In order for the construction sector to progress and track productivity effectively, labor hours need to be documented.

In addition to labor hours to measure productivity, the following metrics will aid in evaluating lifecycle benefits of construction. These include:

- Operational energy performance
- Construction energy and carbon performance
- Waste factors in construction
- Schedule per square foot
- Labor per square foot
- Incidents per square foot
- Change orders per square foot
- Defects per square foot

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APPENDIX A
CASE STUDIES

The following case studies have been developed based on information gathered through questionnaires, interviews, and literature. Missing data left out of the following cases represents data not able to be procured through these methods. Cost information is the adjusted cost to the Washington DC locale in Q1 of 2014. The cost data is also a reflection of the vertical construction cost only; all site improvement, land acquisition, and utility improvements, etc. are not included. Traditional construction comparisons were provided by Cumming Corp.

Of the 18 original case studies, 7 projects had enough information for a comparative analysis.

Those 7 projects are outlined below along with the type of STC used on that project.

PROJECT	STC USED
Bridport House	CLT, GLT
Carlisle Lane Lofts	CLT, GLT
Massive Living	CLT, GLT
SmartLIFE Centre	CLT, GLT
The Long Hall	CLT, GLT
UBC Earth Systems Science Building	CLT, GLT, LSL
UBC Okanagan Fitness & Wellness Center	CLT, GLT

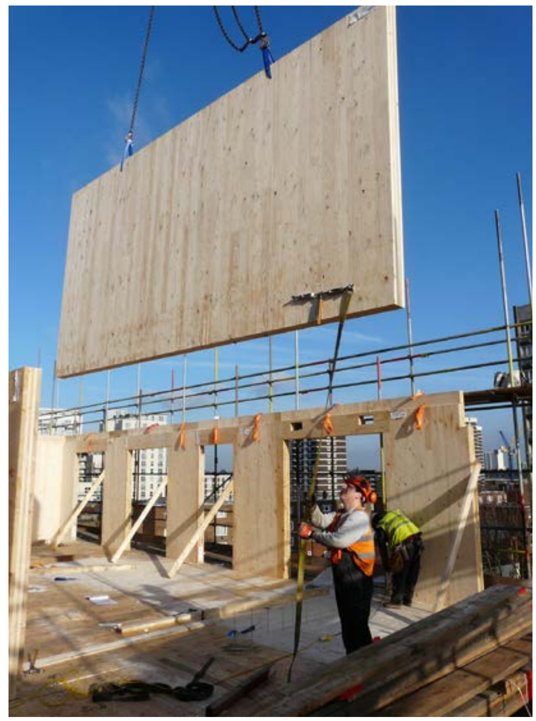
BRIDPORT HOUSE
HACKNEY, UK

Architect: Karakusevic Carson Architects
CLT Supplier: Stora Enso
Contractor: Willmott Dixon Housing

ABOUT

Designed as the first phase of the regeneration of the Colville Estate, Bridport House was commissioned by Hackney Council to replace an original 1950s block with 41 new homes in two joined blocks, one eight stories high and the other five stories.

All elements from the ground floor upwards are CLT – including the lift shaft. Below ground level (the piles, foundations and lift pit) is reinforced concrete.



GENERAL

HOUSING BUILDING TYPE

2011 YEAR COMPLETED

45,424 SQUARE FEET (FT²) (4,220M²)

55,726 TIMBER VOLUME (FT³) (1,578M³)

8 + 5 STORIES TALL

COST

£5.8M CONSTRUCTION COST

£1.2M CLT CONTRACT

SCHEDULE

18 MONTHS FROM START TO FINISH

12 MONTHS UNDER CONSTRUCTION

6 MONTHS FOR DESIGN

6 WEEKS IN FACTORY

14 WEEKS TO ERECT

850 MILES FROM FACTORY TO SITE

COMPARISON

7% MORE COST EFFECTIVE

$198.19* PER S.F.

25% FASTER CONSTRUCTION

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

LESSONS LEARNED

The biggest acclaim for this project was the ability to double the size of the replacement structure with only a 10% increase in overall weight. A summation of the lessons learned provided by the stakeholders interviewed are outlined below:

- Front load even more of the design process to help better streamline the fabrication and construction process.
- Full BIM integration
- Allow designers and specialists to be involved through the entire project to facilitate new methods of construction to completion.

Photo Credits: Karakusevic Carson Architects & Willmot Dixon Housing

REFERENCES

- Mannewitz, Stefan. Karakusevic Carson Architects. Online survey on 8.1.14
- Cook, Steve. Willmott Dixon Housing. Online survey on 9.3.14
- Fovargue, Johnathan. Eurban. Phone interview with Gentry Griffin on 6.11.14

	BRIDPORT HOUSE	COMPARED PROJECT
CONSTRUCTION DURATION	12 MONTHS	16 MONTHS
STORIES AND CONSTRUCTION TYPE	8 STORIES WOOD	4 STORIES WOOD
SQUARE FOOTAGE	45,424	55,000
COST	$9M	$11.7M
COST/SF	$198.23	$213.33

CARLISLE LANE
WATERLOO, LONDON

Architect: Pringle Richards Sharrat Architects
Timber Engineer: Eurban
Contractor: D.F. Keane Builders & Contractors

ABOUT

Four one-bed apartments built on a tight urban site next to the railway viaduct in Waterloo. The site is as narrow as 23 feet in parts and only 66 feet long; the two-story residential development has been built against three existing boundary walls of the previous structure. Each apartment has large windows facing onto a shared courtyard. The lightweight structure avoided the necessity for substantial new foundation works and the prefabricated system facilitated construction within a confined space.

GENERAL

HOUSING BUILDING TYPE

2005 YEAR COMPLETED

1,722 SQUARE FEET (FT²) **(160M²)**

2,295 TIMBER VOLUME (FT³) **(65M³)**

2 STORIES TALL

COST

£355K CONSTRUCTION COST

£26K DESIGN COST

£88K CLT CONTRACT

SCHEDULE

16 MONTHS FROM START TO FINISH

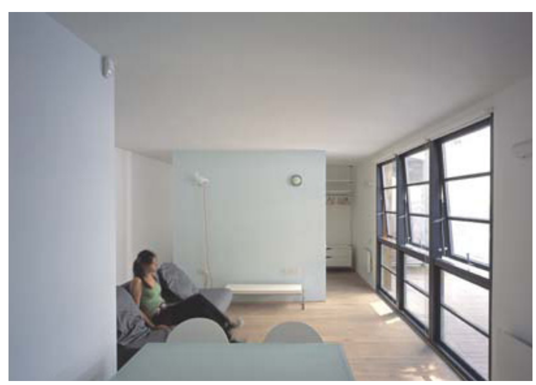
11 MONTHS UNDER CONSTRUCTION

5 MONTHS FOR DESIGN

1 MONTHS IN FACTORY

6 DAYS TO ERECT

671 MILES FROM FACTORY TO SITE



COMPARISON

31% FASTER CONSTRUCTION

$305.28* PER S.F.

43.1% LESS COST EFFECTIVE

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

LESSONS LEARNED

The biggest acclaim for this project was the rapid speed of construction for the CLT. It was assembled in just 6 days. A summation of the lessons learned provided by the stakeholders interviewed are outlined below:

- Be aware of permits needed to travel from state to state
- The cost was said to be competitive to traditional built construction
- Lifetime cost of the project is much better than traditional built construction
- The quality of the panels was very precise creating a very tight envelope
- Overall time spent on the site was drastically reduced.
- CLT allowed for a lightweight/economical foundation
- Careful consideration is needed when detailing the ground floor details where the CLT meets the foundation.

Photo Credit: Pringle Richards Sharrat Architects

REFERENCES

- Pringle, John. Pringle Richards Sharrat Architects. Online Survey on 11.14.13
- Pringle, John. Pringle Richards Sharrat Architects. Interview with Jarrett Moe on 1.31.14
- Keane, Don. D.F. Keane Builders & Contractors. Phone interview with Gentry Griffin on 6.11.14
- Fovargue, Johnathan. Eurban. Online survey response on 7.10.14

	CARLISLE LANE	COMPARED PROJECT
CONSTRUCTION DURATION	11 MONTHS	16 MONTHS
STORIES AND CONSTRUCTION TYPE	2 STORIES WOOD	4 STORIES WOOD
SQUARE FOOTAGE	1,722	55,000
ADJUSTED COST	$525K	$11.7M
COST/SF	$305.28	$213.33

MASSIVE LIVING
GRAZ, AUSTRIA

Architect: Peter Zinganel
CLT Supplier: Holzbau Weiz
Contractor: F+R Bau

ABOUT
On land in the Witten Bauerstrasse two 3-storey buildings were built above common underground parking. Between the two of children's playground has been created and both houses have extensions for garbage and bicycle storage. The remaining open areas were designed as a common green space.
The condominium has 22 apartments that have been built essentially as solid wood construction made of laminated timber

GENERAL

HOUSING BUILDING TYPE

2012 YEAR COMPLETED

28,987 (2,693M²) SQUARE FEET (FT²)

19,776 (560M³) TIMBER VOLUME (FT³)

3 STORIES TALL

COST

€3.2M CONSTRUCTION COST

€700K CLT CONTRACT

SCHEDULE

24 MONTHS FROM START TO FINISH

18 MONTHS UNDER CONSTRUCTION

3 MONTHS FOR DESIGN

1 MONTH IN FACTORY

3 WEEKS TO ERECT

COMPARISON

14% MORE COST EFFECTIVE

$182.50* PER S.F.

0% FASTER CONSTRUCTION

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

Photo Credit: Peter Zinganel & Jorg Konstantinov

REFERENCES

- Ringhofer, Andreas. Institute of Timber Engineering and Wood Technology at Graz University of Technology. Online survey on 6.6.14
- Zinganel, Peter. Peter Zinganel. Online survey on 7.1.14

	MASSIVE LIVING	COMPARED PROJECT
CONSTRUCTION DURATION	18 MONTHS	16 MONTHS
STORIES AND CONSTRUCTION TYPE	3 STORIES WOOD	4 STORIES WOOD
SQUARE FOOTAGE	28,987	55,000
COST	$5.29M	$11.7M
COST/SF	$182.50	$213.33

SMARTLIFE CENTRE
CAMBRIDGE, UK

Architect: Annand & Mustoe Architects
CLT Supplier: Lenlotec
Contractor: Morgan Sindall

ABOUT
A two-story classroom block to house the Smart LIFE network centre in Cambridge. SmartLIFE is a pioneering project lead by Cambridgeshire County Council in partnership with Cambridge Regional College to continue the award winning work of the SmartLIFE project, promoting innovative and sustainable construction in the UK and delivering training in Modern Methods of Construction. The solid timber building accommodates three classrooms, a changing area and a gallery.

GENERAL

ACADEMIC BUILDING TYPE

2005 YEAR COMPLETED

16,307 SQUARE FEET (FT²) **(1,515M²)**

4,590 TIMBER VOLUME (FT³) **(130M³)**

2 STORIES TALL

COST

£2.3M CONSTRUCTION COST

£104K CLT CONTRACT

SCHEDULE

15 MONTHS FROM START TO FINISH

10 MONTHS UNDER CONSTRUCTION

3 MONTHS FOR DESIGN

1 MONTHS IN FACTORY

10 DAYS TO ERECT

724 MILES FROM FACTORY TO SITE

COMPARISON

17% MORE COST EFFECTIVE

$257.92* PER S.F.

41% FASTER CONSTRUCTION

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

Photo Credit: Eurban

REFERENCES

- Vanoli, Michael. Annand & Mustoe Architects. Online survey on 6.24.14
- Fovargue, Johnathan. Eurban. Online survey on 7.10.14

	UK SMARTLIFE	COMPARED PROJECT
CONSTRUCTION DURATION	10 MONTHS	17 MONTHS
STORIES AND CONSTRUCTION TYPE	2 STORIES WOOD	4 STORIES WOOD
SQUARE FOOTAGE	16,307	73,000
COST	$4.2M	$22.8M
COST/SF	$257.92	$312.27

THE LONG HALL
WHITEFISH, MONTANA

Architect: Datum Design Drafting
CLT Supplier: Innovative Timber Systems
Contractor: The Long Hall LLC

ABOUT
The Long Hall is a mixed-use, urban infill project. The building provides retail and business space on the first floor, and the second floor is for a martial arts studio. The building was originally designed to be made with Concrete Masonry Units (CMU). The design team had convinced the owner to build with CLT arguing that it would be a cost-effective alternative to CMU while delivering a high-performance building, more sustainable, with a better design aesthetic.

GENERAL

COMMERCIAL BUILDING TYPE

2011 YEAR COMPLETED

4,863 SQUARE FEET (FT^2) **($452M^2$)**

4,590 TIMBER VOLUME (FT^3) **($130M^3$)**

2 STORIES TALL

COST

$377K CONSTRUCTION COST

13K DESIGN COST

305K CLT CONTRACT

SCHEDULE

6 MONTHS FROM START TO FINISH

2 MONTHS UNDER CONSTRUCTION

4 MONTHS FOR DESIGN

1 MONTHS IN FACTORY

4.5 DAYS TO ERECT

5,132 MILES FROM FACTORY TO SITE

COMPARISON

43% MORE COST EFFECTIVE

$91.19* PER S.F.

83% FASTER CONSTRUCTION

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

LESSONS LEARNED

The biggest acclaim for this project was the rapid speed of construction for the CLT. It was assembled in just 4.5 days. A summation of the lessons learned provided by the stakeholders interviewed are outlined below:

- Be aware of permits needed to transport from state to state. (i.e. weight restrictions)
- Spend more time planning out placement of mechanical and electrical components
- Be aware of the dimensions of a standard shipping container to maximize yield of panels being shipped.
- The accuracy of the measurements were very precise, within 1/8".

Photo Credit: CLT Solutions

REFERENCES

- McCrone, Pete. ITS Smarwoods. Phone interview with Gentry Griffin on 6.5.14
- Hatten, Jason. Datum Design Drafting. Phone interview with Gentry Griffin on 6.5.14
- Hammer, Andy. The Long Hall LLC. Phone interview with Gentry Griffin on 6.11.14
- Byle, Darryl. CLT Solutions LLC. Online survey on 6.23.14

	THE LONG HALL	COMPARED PROJECT
CONSTRUCTION DURATION	2 MONTHS	12 MONTHS
STORIES AND CONSTRUCTION TYPE	2 STORIES WOOD	2 STORIES WOOD
SQUARE FOOTAGE	4,863	46,000
COST	$443K	$7.36M
COST/SF	$91.19	$159.97

UBC EARTH SYSTEMS SCIENCE BUILDING
VANCOUVER, BC

Architect: Perkins + Will
CLT Supplier: Structurlam
Contractor: Bird Construction

ABOUT

This was a pilot project to test the capabilities of solid timber. A variety of materials were used including timber, steel, and concrete. Located on the University of British Columbia (UBC) Vancouver campus, and is home to the Earth, Ocean and Atmospheric Studies, the Department of Statistics, the Pacific Institute for the Mathematical Sciences and the Dean of Science.

GENERAL

ACADEMIC BUILDING TYPE

2012 YEAR COMPLETED

164,020 SQUARE FEET (FT²) **(15,238M²)**

46,509 TIMBER VOLUME (FT³) **(1,317M³)**

6 STORIES TALL

COST

$48.7M CONSTRUCTION COST (CAD)

$6M DESIGN COST (CAD)

$1.6M SOLID TIMBER CONTRACT (CAD)

SCHEDULE

36 MONTHS FROM START TO FINISH

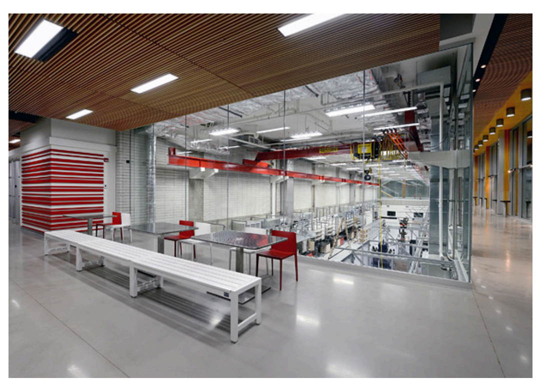
24 MONTHS UNDER CONSTRUCTION

12 MONTHS FOR DESIGN

5 MONTHS IN FACTORY

7 MONTHS TO ERECT

258 MILES FROM FACTORY TO SITE



COMPARISON

11% MORE COST EFFECTIVE

$276.85* PER S.F.

42% SLOWER CONSTRUCTION

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

LESSONS LEARNED

A summation of the lessons learned provided by the stakeholders interviewed are outlined below:

- Lock down the design early
- Have experienced installers install the solid timber
- Pay close attention to material connections (i.e. CLT to steel)

Photo Credit: Martin Tessler
Courtesy of: Perkins + Will

REFERENCES

- Foit, Jana. Perkins + Will. Phone interview with Gentry Griffin on 6.5.2014
- Bangma, Paul. Bird Construction. Phone interview with Gentry Griffin on 6.10.14
- Downing, Bill. Structurlam. Phone interview with Gentry Griffin on 7.15.14

	UBC EARTH SYSTEMS SCIENCE CENTER	COMPARED PROJECT
CONSTRUCTION DURATION	24 MONTHS	16 MONTHS
STORIES AND CONSTRUCTION TYPE	6 STORIES WOOD	4 STORIES WOOD
SQUARE FOOTAGE	164,020	73,000
COST	$48.7M	$22.8M
COST/SF	$276.85	$312.27

UBC OKANAGAN WELLNESS CENTER

KELOWNA, NV

Architect: McFarland Marceau Architects
CLT Supplier: Structurlam
Contractor: Kindred Construction

ABOUT

The new UBCO Fitness and Wellness Centre (FWC) is the result of a design-build project headed by Kindred Construction in partnership with McFarland Marceau Architects. The FWC pavilion, or *The Hangar* as it has come to be known, is attached to the north side of the existing gymnasium complex via a 25 foot wide link and sits at an angle to it, thereby preserving a view down University Walk, the campus' main pedestrian axis and convocation route.

GENERAL

INSTITUTIONAL BUILDING TYPE

2013 YEAR COMPLETED

8,470 SQUARE FEET (FT²) **(812M²)**

11,250 TIMBER VOLUME (FT³) **(319M³)**

2 STORIES TALL

COST

$3.7M CONSTRUCTION COST (CAD)

$430K DESIGN COST (CAD)

$300K CLT CONTRACT

SCHEDULE

24 MONTHS FROM START TO FINISH

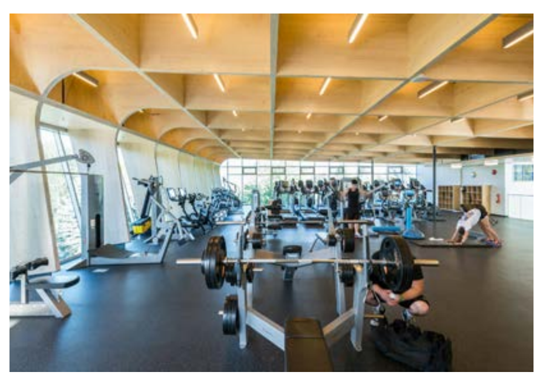
14 MONTHS UNDER CONSTRUCTION

10 MONTHS FOR DESIGN

6 WEEKS IN FACTORY

8 WEEKS TO ERECT

47 MILES FROM FACTORY TO SITE



COMPARISON

21% LESS COST EFFECTIVE

$343.11* PER S.F.

0% FASTER CONSTRUCTION

** Normalized to the first quarter of 2014 in US Dollars and Washington, DC*

Photo Credits: Don Erhardt & McFarland Marceau Architects

REFERENCES

- Maile, Nick. UBC Properties Trust. Online survey on 6.30.14
- Duffield, Craig. Mcfarland Marceau Architects. Phone survey with Gentry Griffin on 7.3.14
- Johnson, Brad. JBR Construction. Online survey on 7.3.14
- Tolnai, Stephen. Structurlam. Phone interview with Gentry Griffin on 7.15.14

	UBC OKANAGAN FITNESS AND WELLNESS CENTER	COMPARED PROJECT
CONSTRUCTION DURATION	14 MONTHS	14 MONTHS
STORIES AND CONSTRUCTION TYPE	2 STORIES WOOD	3 STORIES WOOD
SQUARE FOOTAGE	8,740	65,000
COST	$2.99M	$18.48M
COST/SF	$343.11	$284.25

APPENDIX B
COMPARATIVE ANALYSIS

INTRODUCTION

DESCRIPTION

This analysis compares multiple STC projects to a baseline control project reflecting a traditional construction approach. Analysis of total labor and material costs, total labor hours, and total design and construction schedules have been analyzed to understand the advantages of STC vs. traditional construction methods.

SOURCES USED

The following sources have been used in the course of the study:

- ITAC Study Team providing 11 different solid timber based projects (US and International)
- Davis Bacon Wage Rates
- RS Means Geographical Indices
- RS Means Standard Hourly Rates for the Construction Industry
- Cumming Corporation Internal Econ/Market Report

METHODOLOGY

This comparative analysis uses information provided by the study team for 11 solid timber projects that included raw cost and schedule data. Benchmark traditional projects were identified in the Cumming Corp. database. The solid timber and traditional build cases data was normalized for comparative function. The project team determined that 7 case studies were appropriate for reporting. In doing so, the following variables have been accounted for:

Timeline

All costs take to "current dollars" / Q1 2014 by using the following escalation %s:

2008	-	0.00%
2009	-	0.00%
2010	-	1.50%
2011	-	2.50%
2012	-	3.00%
2013	-	3.50%
2014	-	3.50%

Location

All costs have been modified to reflect current market conditions, labor rates, and taxes in the Washington DC construction market

Site Location

All costs have been modified from either Rural or City Center site locations to "Urban". This adjusts cost and schedule variables for access, laydown, parking, working hour restrictions, etc. to a level play field.

Currency

All costs have been modified to reflect US $.

Quantities

All costs have been reflected over imperial measures ($/SF)

Delivery

All costs have been reflected over imperial measures ($/SF)

BASIS FOR UNIT COSTS

Unit costs are based on current bid prices in the Washington DC area. Subcontractor overhead and profit is included in each line item unit cost. This overhead and profit covers each subcontractor's cost for labor, materials and equipment, sales taxes, field overhead, home office overhead, and profit. The general contractor's overhead and profit is shown separately.

ITEMS EXCLUDED FROM THE ANALYSIS

- Hazardous material abatement
- Utility infrastructure improvements/upsizing
- Professional design and consulting fees
- General building permit
- Testing and inspection fees
- Land acquisition costs

ITEMS AFFECTING THE COST ESTIMATE

- Items that may change the estimated construction cost include, but are not limited to:
- Modifications to the scope of work included in this estimate
- Unforeseen sub-surface conditions
- Restrictive technical specifications or excessive contract conditions
- Any specified item of equipment, material, or product that cannot be obtained from 3 sources
- Any other non-competitive bid situations
- Bids delayed beyond the projected schedule

Comparison Summary (Solid Timber)

Ref	Description	Traditional Construction					Solid Timber Samples									
		Student Res.	Classroom	Office (HR)	Office (LR)	Wellness	Carlisle Lane (Apartments)	Elkford CC (Community)	Long Hall (Comm / Retail)	UBC Earth (Research)	Fort McMurray (Airport)	UBC Okanagan (Wellness)	Forte (Comm / Retail)	Massive Liv. (Residential)	UK Smartlife (Academic)	Bridport (Residential)
1.	SF-age	55,000 SF	73,000 SF	154,960 SF	46,000 SF	65,000 SF	1,722 SF	16,540 SF	4,863 SF	164,020 SF	161,459 SF	8,740 SF	28,524 SF	28,987 SF	16,307 SF	45,424 SF
2.	Stories	5	3	10	2	3	2	1	2	6	3	2	10	3	2	8
3.	Total Cost (USD $)	$11,733,182	$22,795,894	$37,010,974	$7,358,759	$18,476,454	$525,686	$4,573,908	$443,468	$41,380,846	$69,699,847	$2,732,734	$10,099,883	$5,290,087	$4,205,963	$9,004,396
4.	Total Cost / SF	$213.33	$312.27	$238.84	$159.97	$284.25	$512.18	$276.54	$91.19	$252.29	$431.69	$312.67	$354.08	$182.50	$257.92	$198.23
5.	Indirect Cost / SF (USD $)	$27.83	$40.73	$31.15	$20.87	$37.08	$66.81	$36.07	$11.89	$32.91	$56.31	$40.78	$46.18	$23.80	$33.64	$25.86
6.	Material Cost / SF (USD $)	$83.48	$122.19	$93.46	$62.60	$111.23	$166.84	$102.75	$37.47	$84.72	$172.59	$116.54	$121.63	$79.03	$94.15	$71.78
7.	Labor Cost / SF (USD $)	$102.03	$149.35	$114.23	$76.51	$135.95	$278.53	$137.71	$41.83	$134.66	$202.79	$155.34	$186.27	$79.67	$130.13	$100.59
8.	Total Labor Hours	97,208	188,862	306,633	60,967	153,076	6,522	30,756	3,498	309,902	516,352	18,418	77,479	36,631	34,500	74,352
9.	Labor Hours / SF	1.77	2.59	1.98	1.33	2.36	3.79	1.86	0.72	1.89	3.20	2.11	2.72	1.26	2.12	1.64
10.	Construction in place / month	$733,324	$1,139,795	$2,177,116	$2,452,920	$1,026,470	$47,790	$190,579	$221,734	$1,724,202	$1,936,107	$195,195	$918,171	$293,894	$420,596	$750,366
11.	Mod vs Traditional Labour Hours / SF Comparison						1.77	2.59	1.33	2.59	TBD	2.36	1.98	1.77	2.59	1.77
12.	Other Considerations						Tight Site Retrofit	Winterization	Tight Site	-	Rural Premium Fdns		Tight F/print x 10 Story			

Key Comparative Considerations:

# of Stories: Affects structure size & type, wind loads, floor:skin ratios, glazed : non glazed surfaces, heat gain.

SF-age: Affects building efficiences, grossing factors, economies of scale, opportunities for repetition.

Local Market Conditions: The above assume typical bid conditions but each project would be open to key variables depending on time of bid, project size, labor availability, bid instructions, perceived risk, competing workload.

Limitations - Project Variables Not Yet "Levelled"

Project Size: The traditional construction benchmarks are representative of similar project "types" to the modular samples. Variances in overall SF-age, height, and configuration can affect economies of scale, building component relationships (eg - skin:floor ratio), wind loads, seismic considerations, project access, and labor productivity.

SF-age Program: The traditional construction benchmarks are representative of similar project "types" to the modular samples. Variances in program "make up" do exist such as comparing a retail sample with a retail : bank modular project.

Delivery Method: Each sample project will utilize variations on delivery method (design-bid-build, CM@Risk, negotiated, design-build). Each delivery model affects initial and final construction costs differently.

Bid Timing: We have not differentiated the above samples for any seasonal bidding trends. Q4 bids typically fall into the "optimum bid cycle" which can yield 3 - 5% in savings, spring and summer bids can trend the opposite.

* Assumes an equal spread of construction in place per month.

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - Carlisle Lane Residences

#	Description	Carlisle Lane Residences Quantative Analysis				Baseline "Traditional" Comparison - Residence Quantative Analysis			
		Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Residences				Student Residence			
	Construction	2 Story				4 Story / Wood			
	Location	Waterloo, London				Washington DC			
	Timeline	2005				Q1 / 2014			
	Construction Schedule	11 Months				16 Months			
	GSF		1,722 SF				55,000 SF		
	Base Cost			**£355,000**	**£206.16**			**$11,733,182**	**$213.33**
	Adjusted Cost (see o/leaf)			**$525,686**	**$305.28**			**$11,733,182**	**$213.33**
1b	**Comparison**								
	Total Costs								
	Sitework			$262,843	$152.64			$1,183,744	$21.52
	Shell / Core			$210,275	$122.11			$5,356,392	$97.39
	Interior Fit Out			$52,569	$30.53			$5,193,046	$94.42
	GC Indirect Costs			incl above	incl above			incl above	incl above
				$525,686	**$305.28**			**$11,733,182**	**$213.33**
	Direct Cost Only								
	Labor / Equipment			$224,405	$130.32			$5,611,522	$102.03
	Materials (+ taxes)			$232,714	$135.14			$4,591,245	$83.48
	Labor Hours / Hours per SF			6,522	3.79			$97,208	1.77
	Schedule - Design			5 Months	-			7 Months	-
	Schedule - Construction			11 Months	-			12 Months	-

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - The Long Hall

#	Description	The Long Hall Quantative Analysis				Baseline "Traditional" Comparison - Office (Low Rise) Quantative Analysis			
		Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Commercial				Office Low Rise			
	Construction	2 Story				2 Story			
	Location	Whitefish, MT				Washington DC			
	Timeline	Q2 / 2011				Q1 / 2014			
	Construction Schedule	2 Months				12 Months			
	GSF		4,863 SF				46,000 SF		
	Base Cost			**$376,966**	**$77.52**			**$7,358,759**	**$159.97**
	Adjusted Cost (see o/leaf)			**$443,468**	**$91.19**			**$7,358,759**	**$159.97**
1b	**Comparison**								
	Total Costs								
	Sitework			$44,347	$9.12			$323,617	$7.04
	Shell / Core			$221,734	$45.60			$3,257,244	$70.81
	Interior Fit Out			$177,387	$36.48			$3,777,898	$82.13
	GC Indirect Costs			incl above	incl above			incl above	incl above
				$443,468	**$91.19**			**$7,358,759**	**$159.97**
	Direct Cost Only								
	Labor / Equipment			$201,950	$41.53			$3,519,407	$76.51
	Materials (+ taxes)			$183,674	$37.77			$2,879,514	$62.60
	Labor Hours / Hours per SF			3,498	0.72			60,967	1.33
	Schedule - Design			4 Months	-			5 Months	-
	Schedule - Construction			2 Months	-			12 Months	-

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - UBC Earth Systems Science Building

		UBC Earth Systems Science Building Quantative Analysis				Baseline "Traditional" Comparison - Classroom Quantative Analysis			
#	Description	Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Science / Research				Classroom			
	Construction	6 Story				4 Story			
	Location	Vancouver, BC				Washington, DC			
	Timeline	2012				Current			
	Construction Schedule	24 Months				17 Months			
	GSF		164,020 SF				73,000 SF		
	Base Cost			**$48,700,000**	**$296.92**			**$22,795,894**	**$312.27**
	Adjusted Cost (see o/leaf)			**$45,409,285**	**$276.85**			**$22,795,894**	**$312.27**
1b	**Comparison**								
	Total Costs								
	Sitework			$22,704,642	$138.43			$1,085,519	$14.87
	Shell / Core			$18,163,714	$110.74			$10,090,259	$138.22
	Interior Fit Out			$4,540,928	$27.69			$11,620,116	$159.18
	GC Indirect Costs			incl above	incl above			N/A	N/A
				$45,409,285	**$276.85**			**N/A**	**N/A**
	Direct Cost Only								
	Labor / Equipment			$19,631,147	$119.69			$10,902,384	$149.35
	Materials (+ taxes)			$19,855,187	$121.05			$8,920,132	$122.19
	Labor Hours / Hours per SF			309,902	1.89			$188,862	$2.59
	Schedule - Design			12 Months	-			7 Months	N/A
	Schedule - Construction			24 Months	-			17 Months	N/A

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - UBC Okanagan Fitness / Wellness Center

#	Description	UBC Okanagan Fitness / Wellness Center Quantative Analysis				Baseline "Traditional" Comparison Quantative Analysis			
		Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Wellness Facility				Student Health			
	Construction	2 Story				3 Story			
	Location	Kelowna, BC				Washington, DC			
	Timeline	Q2 / 2013				Current			
	Construction Schedule	14 Months				14 Months			
	GSF		8,740 SF				65,000 SF		
	Base Cost			**$3,360,000**	**$384.44**			**$18,476,454**	**$284.25**
	Adjusted Cost (see o/leaf)			**$2,998,767**	**$343.11**			**$18,476,454**	**$284.25**
1b	**Comparison**								
	Total Costs								
	Sitework			$1,499,383	$171.55			$879,831	$13.54
	Shell / Core			$1,199,507	$137.24			$8,178,325	$125.82
	Interior Fit Out			$299,877	$34.31			$9,418,298	$144.90
	GC Indirect Costs			incl above	incl above			N/A	N/A
				$2,998,767	**$343.11**			**$18,476,454**	**$284.25**
	Direct Cost Only								
	Labor / Equipment			$1,166,710	$133.49			$8,836,565	$135.95
	Materials (+ taxes)			$1,440,913	$164.86			$7,229,917	$111.23
	Labor Hours / Hours per SF			18,418	2.11			153,076	2.36
	Schedule - Design			10 Months	-			9 Months	N/A
	Schedule - Construction			14 Months	-			14 Months	N/A

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - Smartlife Centre

#	Description	UK Smartlife (Academic Facility) Quantative Analysis				Baseline "Traditional" Comparison - Classroom Quantative Analysis			
		Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Academic Facility				Classroom			
	Construction	2 Story				4 Story			
	Location	Cambridge, UK				Washington, DC			
	Timeline	2005				Current			
	Construction Schedule	10 Months				17 Months			
	GSF		16,307 SF				73,000 SF		
	Base Cost			**£2,270,000**	**£139.20**			**$22,795,894**	**$312.27**
	Adjusted Cost (see o/leaf)			**$4,205,963**	**$257.92**			**$22,795,894**	**$312.27**
1b	**Comparison**								
	Total Costs								
	Sitework			$2,102,982	$128.96			$1,085,519	$14.87
	Shell / Core			$1,682,385	$103.17			$10,090,259	$138.22
	Interior Fit Out			$420,596	$25.79			$11,620,116	$159.18
	GC Indirect Costs			incl above	incl above			N/A	N/A
				$4,205,963	**$257.92**			**N/A**	**N/A**
	Direct Cost Only								
	Labor / Equipment			$1,991,549	$122.13			$10,902,384	$149.35
	Materials (+ taxes)			$1,535,309	$94.15			$8,920,132	$122.19
	Labor Hours / Hours per SF			34,500	2.12			$188,862	$2.59
	Schedule - Design			3 Months	-			7 Months	N/A
	Schedule - Construction			10 Months	-			17 Months	N/A

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - Bridport House

#	Description	Bridport House (Residential) Quantative Analysis				Baseline "Traditional" Comparison - Residence Quantative Analysis			
		Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Residential				Student Residence			
	Construction	8 Story				4 Story / Wood			
	Location	Hackney, UK				Washington DC			
	Timeline	2011				Q1 / 2014			
	Construction Schedule	12 Months				16 Months			
	GSF		45,424 SF				55,000 SF		
	Base Cost			**£5,800,000**	**£127.69**			**$11,733,182**	**$213.33**
	Adjusted Cost (see o/leaf)			**$9,004,396**	**$198.23**			**$11,733,182**	**$213.33**
1b	**Comparison**								
	Total Costs								
	Sitework			$4,502,198	$99.11			$1,183,744	$21.52
	Shell / Core			$3,601,758	$79.29			$5,356,392	$97.39
	Interior Fit Out			$900,440	$19.82			$5,193,046	$94.42
	GC Indirect Costs			incl above	incl above			incl above	incl above
				$9,004,396	**$198.23**			**$11,733,182**	**$213.33**
	Direct Cost Only								
	Labor / Equipment			$4,292,113	$94.49			$5,611,522	$102.03
	Materials (+ taxes)			$3,260,642	$71.78			$4,591,245	$83.48
	Labor Hours / Hours per SF			74,352	1.64			$97,208	$1.77
	Schedule - Design			6 Months	-			7 Months	-
	Schedule - Construction			12 Months	-			12 Months	-

Solid Timber Construction Analysis
Cost & Schedule Comparison (Rev 3)
Various Locations, USA + International
High Level $ / SF Analysis

Project No: 14-00061.00
Date: 09/16/14

Solid Timber Summary / Comparison - Massive Living (Residential)

		Massive Living (Residential) Quantative Analysis				Baseline "Traditional" Comparison - Housing Quantative Analysis			
#	Description	Info	Unit	Total	Total / SF	Info	Unit	Total	Total / SF
1a	**Base Information**								
	Type	Residential				Student Residence			
	Construction	3 Story				4 Story / Wood			
	Location	Graz, Austria				Washington DC			
	Timeline	2011				Q1 / 2014			
	Construction Schedule	18 Months				16 Months			
	GSF		28,987 SF				55,000 SF		
	Base Cost			**£3,200,000**	**£110.39**			**$11,733,182**	**$213.33**
	Adjusted Cost (see o/leaf)			**$5,290,087**	**$182.50**			**$11,733,182**	**$213.33**
1b	**Comparison**								
	Total Costs								
	Sitework			$2,645,043	$91.25			$1,183,744	$21.52
	Shell / Core			$2,116,035	$73.00			$5,356,392	$97.39
	Interior Fit Out			$529,009	$18.25			$5,193,046	$94.42
	GC Indirect Costs			incl above	incl above			incl above	incl above
				$5,290,087	**$182.50**			**$11,733,182**	**$213.33**
	Direct Cost Only								
	Labor / Equipment			$2,114,572	$72.95			$5,611,522	$102.03
	Materials (+ taxes)			$2,290,786	$79.03			$4,591,245	$83.48
	Labor Hours / Hours per SF			36,631	1.26			97,208	1.77
	Schedule - Design			3 Months	-			7 Months	-
	Schedule - Construction			18 Months	-			12 Months	-

ABOUT ITAC

The Integrated Technology in Architecture Center at the University of Utah's College of Architecture + Planning is an agent of change toward better buildings.

Faculty and students in the center conduct research on buildings that are more construction efficient and energy efficient throughout their life cycle.

ITAC conducts activities with academic and industry partners, provides education in the form of teaching and workshops, and conducts outreach with university and community groups.

Expertise

- Research and development of sustainable building technologies through a holistic approach
- Off-site, modern methods of construction, and lean construction
- Optimization, energy efficiency strategies through passive design tactics
- Inquiry into digital workflow, parametric modeling, and BIM
- Study of integrated practice, collaboration and architect as leader in project delivery
- Knowledge management and transfer of innovative construction processes and products

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SOLID TIMBER CONSTRUCTION
PROCESS, PRACTICE, PERFORMANCE