

Constructing Our Environments:
A Material Comparison

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis.
This is a true copy of the thesis, including any required
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I understand that my thesis may be made electronically
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Abstract

Our built environment is constantly adapting to changing factors: technology, the state of the economy, material resource availability, and, in turn, environmental conditions. The latter has gained notable importance in popular discourse, and especially in the architecture and construction professions. However, as much as we see terms such as “sustainability” and “green” in our everyday lives, government and industry are slow to take action investing in our future environment. Material resources in the building industry are worth investigating.

Timber, used as a structural material to compete with concrete and steel, brings more energy efficient and natural renewable resources to our growing cities. In order to provide a broader perspective of how we as a society use concrete, steel, and timber, I will compare the three building materials in a four part guideline: *Environmental Performance*, *Ease of Manufacture*, *Organized Assembly*, and *Design Flexibility*. Each section provides insight into how we shape these three materials. I argue, based on the rating evaluation, for the benefits, using cross-laminated timber in cities like Toronto.

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Most of all I would like to thank my family, for your constant encouragement and support.

Dedicated to my family

Table of Contents:

Authors Declaration	ii
Abstract	v
Acknowledgements	vii
Dedication	ix
Table of Contents	xi
List of Illustrations	xii
Introduction	1
Background	2
Guidelines	8
<i>1.0 Environmental Performance</i>	21
<i>2.0 Ease of Manufacture</i>	41
<i>3.0 Organized Assembly</i>	69
Case Study - Kaden Klingbeil Architects - E3 Berlin	82
<i>4.0 Design Flexibility</i>	87
Developments in Building Culture	90
Design Parameters	100
Case Study - ACME Architects - Hunsett Mill House	106
Case Study - SOM - The Timber Tower Research Project	110
Cross-laminated Timber in Toronto	114
Moving Forward - Twigsort Application	132
Conclusion	138
Bibliography	140

List of Illustrations

Page No. Figure No. Title & Source

Introduction:

- | | | |
|---------------------------------------|------|---|
| 4 | 0.1 | Downtown Toronto construction boom. Photo by Jim Crocker, 2008.
Source: https://www.flickr.com/photos/jcspics/with/2894161075 . |
| 5 | 0.2 | 10-Storey mixed-use CLT development proposal in London by Hawkins Brown Architects. Source: http://www.archdaily.com/414977/wenlock-road-mixed-use-development-proposal-hawkins-brown-architects/ . |
| 5 | 0.3 | Ibid. |
| 6 | 0.4 | Art Stable urban infill residential project in Seattle using steel framing by Olson Kundig Architects. Source:
http://www.archdaily.com/91356/art-stable-olson-kundig-architects/ . |
| 6 | 0.5 | Ibid. |
| 7 | 0.6 | adAPT New York City 'My Micro Apartment' by nARCHITECTS. Source: http://ny.curbed.com/archives/2013/01/22/new_york_citys_future_microapartment_revealed.php . |
| 7 | 0.7 | Ibid. |
| 9 | 0.8 | View of Downtown Toronto construction. Photo by Torstar News Service. Source:
http://metronewsca.files.wordpress.com/2013/09/condo.jpg |
| 10 | 0.9 | CLT Panels. Source: http://www.recycledarchitecture.com/2011_03_01_archive.html . |
| 11 | 0.10 | CLT Structurlam plant in Okanagan Falls, BC. Source:
https://www.flickr.com/photos/bcgovphotos/5843270011/ . |
| 11 | 0.11 | CLT Structurlam panel assembly. Source:
https://www.flickr.com/photos/structurlam/8457180290/ . |
| 13 | 0.12 | 8-Storey residential CLT building - Bridport House in East London by Karakusevic Carson Architects. Source:
http://www.promolegno.com/progetti/residenza/bridport-house/ . |
| 13 | 0.13 | Structural 3D model, CLT supplied by Stora Enso. Source: http://www.ttjonline.com/features/raising-the-profile-071412/image/raising-the-profile-071412-2.html . |
| 15 | 0.14 | Material guideline rating chart. Drawing by Author. |
| 19 | 0.15 | Collective Intelligence design approach diagram by Kieran Timberlake Architects. Source:
http://gsappworkflow2012.wordpress.com/2012/09/22/theme-1-positioning-architects-in-an-integrated-industry/ . |
| 1.0 Environmental Performance: | | |
| 22,23 | 1.1 | FSC global certified area by country, 2013. (There are other forest certificates besides FSC). Diagram by author. Source: dk.fsc.org/download.august-2012-februar-2013.885.pdf . |
| 25 | 1.2 | LCA diagram for CLT. Drawing by Author. |

<i>Page No.</i>	<i>Figure No.</i>	<i>Title & Source</i>
27	1.3	Global forest cover by millions of hectares. Diagram by Building Information Foundation, RTS. Source: Building Information Foundation, RTS.
27	1.4	U.S. energy consumption by sector. Diagram by U.S. Energy Information Administration. Source: http://architecture2030.org/ .
27	1.5	Building material CO2 production comparison. Diagram by Building Information Foundation, RTS. Source: Building Information Foundation, RTS.
28	1.6	Canadian forest and certified areas, 2013. Diagram by Certification Canada. Source: http://www.certificationcanada.org/index.php/english .
29	1.7	Forest certification types in Ontario, 2013. Diagram by Certification Canada. Source: http://www.certificationcanada.org/index.php/maps-en/provincial/on .
31	1.8	Cross-laminated timber panel configuration. Diagram by FPIInnovations. Source: CLT Handbook.
31	1.9	Interlocking cross-laminated timber (ICLT) panels. Photo by Joe Mayo. Source: http://timbercity.wordpress.com/ .
32	1.10	Ontario coniferous forest region, 2009. Photo by Paul Henman. Source: http://paulhenmanphotography.com/2009/04/27/archway/
33	1.11	Building materials that can be produced for one ton of CO2. Diagram by Materials Council UK. Source: http://www.inthescaleofcarbon.com/
34	1.12	Wood, steel, and concrete LCA CO2 emissions. Diagram by FAO. Source: http://www.fao.org/home/en/
34	1.13	Energy cost during material production. Diagram by unknown author. Source: http://www.timberbuilt.com.au/images/other/energycostlarge.gif .
2.0 Ease of Manufacture:		
42, 43	2.1	Annual production of cement, iron ore (tons) and CLT (sq. m) based on location of manufacturer and total percentage. Diagram by Author. Source: 1. http://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2011-cemen.pdf 2. http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/mcs-2012-feore.pdf 3. http://worldhistoryatyhs.wikispaces.com/file/view/china-map-6.jpg/31457541/china-map-6.jpg 4. http://upload.wikimedia.org/wikipedia/commons/8/82/Simplified_world_mining_map_1.png
46	2.2	Log barge transport in Vancouver, 2006. Photo by Barnaby Dorfman. Source: https://www.flickr.com/photos/bdorfman/149861095/
47	2.3	Heavy timber processing plant. Photo by unknown. Source: http://www.acora.com.au/ .
48, 49	2.4	CLT production process. Diagram by author.
50	2.5	Map of Chantiers-Chiboumamau to Toronto. Diagram by author.

<i>Page No.</i>	<i>Figure No.</i>	<i>Title & Source</i>
51	2.6	Aerial view of Chantiers Chibougamau timber facility in partnership with Nordic. Photo by Chantiers Chibougamau Ltd. Source: http://www.chibou.com/english/bienvenue.html
51	2.7	Interior view of facility. Ibid.
53	2.8	Limestone quarry in Japan from Lime Hills #22916, 1988. Photo by Naoya Hatakeyama. Source: http://artblart.com/tag/naoya-hatakeyama-lime-hills/ .
54, 55	2.9	Concrete manufacturing process. Diagram by author.
56	2.10	Still from Twenty-Four Blasts film by Naoya Hatakeyama, 2011. Photo by Naoya Hatakeyama. Source: http://drystonegarden.com/wp-content/uploads/2012/10/NaoyaHatakeyamablasts.jpg
57	2.11	Limestone and sand mining process in Somerset, Kentucky. Photo by unknown. Source: http://www.majorwire.cc/en/content/customer-solutions .
58	2.12	Concrete plant in North Chicago, 2009. Photo by Michael Dant. Source: https://www.flickr.com/photos/faasdant/3750100091/
59	2.13	Concrete pour, 2013. Photo by Elliott Zone. Source: http://urbantoronto.ca .
61	2.14	Iron Ore mining in China, 2012. Photo by unknown. Source: http://www.chinamining.org/News/2012-10-15/1350281962d59391.html
61, 63	2.15	Steel production process. Diagram by author.
64	2.16	Steel production process - oxygen converter ladle. Photo by unknown. Source: http://blog.cleveland.com/business/2008/05/steel1.jpg
65	2.17	Steel production process - billet. Photo by unknown. Source: http://4.bp.blogspot.com/-gGBWly5z7so/UCeg-7mYa5I/AAAAAAAAACg/wlRqU_jNgPU/s1600/ccd.jpg
66	2.18	Global flows of steel and aluminum, 2008. Diagram by Cullen and Allwood, University of Cambridge. Source: http://www.lcmp.eng.cam.ac.uk/wp-content/uploads/T2-Report-web.pdf .
3.0 Organized Assembly:		
70	3.1	CLT assembly. Photo by KLH UK. Source: http://timberfirst.wordpress.com/2012/08/ .
70, 71	3.2	One Bloor East foundation concrete pour, 2013. Photo by Jack Landau. Source: http://urbantoronto.ca/news/2013/01/big-pour-turns-heads-one-bloor-east-0 .
71	3.3	Hearst tower steel assembly. Photo by Foster and Partners. Source: http://www.fosterandpartners.com/projects/hearst-tower/ .
74	3.4	Wall to wall and ceiling to wall connections. Diagram by KLH UK. Source: http://www.klhuk.com/media/30351/klh_component%20catalogue%20for%20cross%20laminated%20timber%20structures_version%2001_2011.pdf .

Page No.	Figure No.	Title & Source
74	3.5	Typical maximum dimensions for CLT panels and flatbed truck. Diagram by author.
74	3.6	Half-lapped panel to panel connection. Photo by CrossLam Timber Solutions LLC. Source: http://cltresources.com/new/html/index.html
75	3.7	Panel to panel double internal spline connection. Photo by Kevin Meechan. Source: https://fpinnovations.ca/Pages/home.aspx
75	3.8	Beam grip for tightening connections. Adjustable steel shores during assembly. Photo by FPInnovations. Source: CLT Handbook by FPInnovations.
76	3.9	BIM and construction process diagrams. Drawing by Kaufmann and Nerding, ed. Source: Building with Timber: Paths Into The Future.
76	3.10	BIM CLT modeling software. Photo by Bastian Kuhn. Source: https://www.dlupal.de/blog/10502/dlupal-rfem-5-modeling-cross-laminated-timber-structures-3/
77	3.11	Production and assembly of timber wall elements. Photos by Kaufmann and Nerding, ed. Source: Building with Timber: Paths Into The Future.
79	3.12	Condo NY2 development concrete construction in Toronto. Photo by Jack Landau. Source: http://urbantoronto.ca/news/2013/12/one-year-work-daniels-ny2 .
79	3.13	Wood formwork being taken off in-situ concrete wall. Photo by unknown. Source: http://2.bp.blogspot.com/-DQRgFe0Mqnk/TZt4u5_4FTI/AAAAAAAAAFA/87rrmfsjuiE/s1600/modern+design+home+concrete+wall.jpg
81	3.14	Ironworker connecting a steel plate to a column at One World Trade Center in NY, 2010. Photo by Mark Lennihan. Source: http://www.salon.com/2012/04/29/with_an_asterisk_wtc_is_back_on_top_in_nyc/ .
81	3.15	Steel frame assembly erection at HL23 in NY by Neil M. Denari Architects, 2009. Photo by author.
83	3.16	E3 residential apartment under construction in Berlin. Photo by Kaden Klingbeil Architekten. Source: http://architecturelab.net/2009/10/e_3-housing-in-berlin-by-kaden-klingbeil-architekten/#lightbox/1/ .
83	3.17	Detail of engineered timber post and beam with metal plate connections. Photo by ibid. Source: ibid.
84	3.18	View of the front facade. Photo by ibid. Source: ibid.
84	3.19	View of the back facade. Photo by ibid. Source: ibid.
85	3.20	View of the interior. Photo by ibid. Source: ibid.

4.0 Design Flexibility:

88, 89	4.1	Aerial view of Hull-Oakes Lumber Co. with expansion plans for new saw technology in Benton, Oregon, 1957. Photo by Gary Tarleton. Source: http://www.loc.gov/pictures/item/or0449.photos.355006p/ .
91	4.2	Graph showing forest land coverage in England over 1000 year period. Diagram by Forestry Commission, England. Source: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221023/pb13871-forestry-policy-statement.pdf .

<i>Page No.</i>	<i>Figure No.</i>	<i>Title & Source</i>
91	4.3	World manufacturing outputs showing 5 countries. Diagram by Financial Times research. Source: http://blogs.rftdata.co.uk/businessblog/files/2012/06/manufacturing.jpg .
92	4.4	Aftermath of fire in Toronto at Bay St. and Wellington St., 1904. Photo by Henry Fowlds Sharpe. Source: http://www.torontopubliclibrary.ca/detail.jsp?Entt=RDMDDC-PICTURES-R-1850&R=DC-PICTURES-R-1850 .
92	4.5	View from street level. Photo by unknown. Source: http://www.torontopubliclibrary.ca/detail.jsp?Entt=RDMDDC-PICTURES-R-1834&R=DC-PICTURES-R-1834 .
93	4.6	The office building of the Architectural Iron Works, 42 Duane Street, NY. Drawing by D.D. Badger and Co. Source: Badger's Illustrated Catalogue of Cast-Iron Architecture.
93	4.7	Elevation and section of Iron Front for Dwelling-house. Drawing by D.D. Badger and Co. Source: <i>ibid.</i>
95	4.8	CO2 emissions from fossil fuel use and cement production per capita. Diagram by EDGAR 4.2. Source: http://www.pbl.nl/en/dossiers/climatechange/faqs .
95	4.9	Cement production by country over a 100 year period. Diagram by Marland et al. Source: http://themasites.pbl.nl/tridion/en/themasites/hyde/productiondata/cement/index-2.html .
98	4.10	School complex in Rillieux-la-Pape, France by Tectoniques Architects. Photo by Renaud Araud. Source: http://www.archdaily.com/397444/school-complex-in-rillieux-la-pape-itectoniques-architects/ .
98	4.11	<i>Ibid.</i>
98	4.12	House in Madrid, Spain by Elii and KLH. Photo by KLH. Source: https://www.behance.net/gallery/House-of-Would-PEDREZUELA-MadridSpain/14428607 .
98	4.13	Residential building in Altura, Spain by Ramon Llobera i Serentill Arquitecte. Photo by KLH. https://www.behance.net/gallery/Residential-building-CAVALLERS-in-AlturaSpain/14428271 .
99	4.14	Residential house in Koniz, Switz., by Halle 58 Architects. Photo by Halle 58 Architects. Source: http://www.halle58.ch/www/php/projekte/085.php .
99	4.15	Library and culture centre in Vennessla, Norway by Helen & Hard. Photo by Emile Ashley. Source: http://www.archdaily.com/209340/vennessla-library-and-culture-house-helen-hard/ .
99	4.16	<i>Ibid.</i>
99	4.17	The Hive library in Worcester, England by Feilden Clegg Bradley Studios. Photo by Hufton & Crow. Source: http://www.archdaily.com/225962/the-hive-feilden-clegg-bradley-studios/ .
99	4.18	<i>Ibid.</i>
98	4.19	<i>Ibid.</i>
98	4.20	House in Wohnbuhne am Hang by DI Ulli Koller and Thomas Stiegler. Photo by KLH. Source: http://www.klh.at/en/projects/family-houses/wohnbuehne-am-hang.html#&panel1-1 .

<i>Page No.</i>	<i>Figure No.</i>	<i>Title & Source</i>
99	4.21	Ibid.
101	4.22	Sectional cellular view of soft wood. Photo by Paulo Monteiro. Source: http://smartmaterials2009.blogspot.ca/2009/09/wood_14.html .
99	4.23	Interior skylight of The Hive library by Feilden Clegg Bradley Studios. Photo by Hufton & Crow. Source: http://www.archdaily.com/225962/the-hive-feilden-clegg-bradley-studios/ .
103	4.24	Fire testing on three-ply cross laminated timber panel. Photo by FPInnovations. Source: http://continuingeducation.construction.com/article.php?L=312&C=1138&P=10 .
107	4.25	CLT panel digital model for Hunsett Mill house in Norfolk, England by ACME. Photo by Cristobal Palma. Source: http://www.archdaily.com/90094/hunsett-mill-acme/ .
107	4.26	CLT assembly and construction. Photo by ibid. Source: ibid.
108	4.27	Ibid
108	4.28	Ibid
109	4.29	Ibid
109	4.30	Ibid
111	4.31	Exterior view of Stantec office building on Spadina and Wellington, Toronto - example of adaptive reuse, formerly the McGregor Socks factory built in 1905 with heavy timber framing. Photo by Richard Johnson. Source: http://www.livewithculture.ca/architecture/doors-open-toronto-preview-stantec-raises-the-green-standard/ .
111	4.32	View of office interior. Photo by Stantec. Source: ibid.
112	4.33	SOM's Timber Tower Research Project, Chicago. Drawing by SOM. Source: http://www.archdaily.com/384032/the-timber-tower-research-project-re-imagining-the-skyscraper/ .
113	4.34	Ibid
115	4.35	Diagram of Toronto's west end neighborhood with potential infill sites. Diagram by author.
116	4.36	West Queen West Triangle developments in former parking lot. Photo by author.
117	4.37	Panoramic view of triangle site at 24 Howard Park Ave. with existing auto repair shop. Photo by author.
117	4.38	Proposed Howard Park Condos by Raw Architects. Rendering by Raw Architects. Source: http://www.rawdesign.ca/
118	4.39	Typical Toronto residential block with subdivided narrow lots. Diagram by author.
119	4.40	Narrow lot total area for one to four story building. Diagram by author.

<i>Page No.</i>	<i>Figure No.</i>	<i>Title & Source</i>
120	4.41	Aerial view of site and surroundings. Photo by Bing Maps.
120	4.42	View of site looking north along Bathurst St. Photo by author.
121	4.43	View of site with height massing. Drawing by author.
123	4.44	Site diagram of site. Drawing by author.
124	4.45	Sketches of massing and residential units. Drawing by author.
125	4.46	Massing diagrams with varying set-backs. Drawing by author.
126	4.47	CLT panels assembled on-site. Photo by KLH UK. Source: http://timberfirst.wordpress.com/2012/08/ .
127	4.48	CLT panels assembled into modules for BMW Ammerwald Hotel in Tyrol by Oskar Leo Kaufmann. Photo by Adolf Bereuter. Source: http://detail-online.com/inspiration/hotel-near-reutte-106094.html .
127	4.49	Hotel room modules assembled on-site. Photo by <i>ibid</i> . Source: <i>ibid</i> .
128	4.50	Integrated business plan diagram with architect/developer working with clients. Drawing by author.
130, 131	4.51	1079 Bathurst Street development pro forma with site acquisition and cost breakdown. Document by author.
133	4.52	Screenshot of Twigsort Material Database prototype website. Photo by Twigsort: Henry Murdock, Saeran Vasanthakumar, Andrea Hunniford, Mark Tam. Image credits: JCDA, Sheida Shahi, May Wu.
134	4.53	Weathered timber post and metal bolt. Photo by author.
136	4.54	Ontario coniferous forest region, 2009. Photo by Paul Henman. Source: http://paulhenmanphotography.com/2009/04/27/archway/ .
136	4.55	5-Ply CLT Panel. Photo by Naturally Wood. Source: http://www.naturallywood.com/emerging-trends/cross-laminated-timber-clt .
137	4.56	Interior of Hunsett Mill house in Norfolk, England by ACME. Photo by Cristobal Palma. Source: http://www.archdaily.com/90094/hunsett-mill-acme/ .
139	4.57	Rings of tree trunk. Photo by author.

1.0 Introduction

Background

I first became interested in material assembly and composition while working at various firms during my education. While producing preliminary design drawings and details for construction documents, I felt disconnected from the physical system, how individual parts were assembled to form the whole. Working for a cabinetmaker and a design/build fabrication studio helped to establish fundamental knowledge for smaller scale assemblies, but I was still curious to know more about material innovation as well as the construction process.

Before entering the University of Waterloo Masters of Architecture program I briefly worked with the Cooper Union Institute for Sustainable Design on a photography exhibition entitled, “Landscapes of Extraction: The Collateral Damage of the Fossil Fuel Industries” by J Henry Fair. While researching and producing diagrams I became interested in how we manufacture everyday objects, especially standard architectural materials, from raw minerals to refined products.

The “how” of the design and building process plays an essential role in the success of the overall execution. I find myself asking how economics affects the design and construction period, because, in many cases, the budget is a driver in decision making. It is important to understand the use of building materials and how they are produced. In designing and constructing for quality it is important to understand the context of the site, performance of materials and assembly, and the financial intentions of development.

I became interested in heavy timber structures and cross-laminated timber while attending lectures by Alex de Rijke of DRMM architects and Charles Walker of Royal College of Art and formerly of the Advanced Geometry Unit at Ove Arup

and Partners. New techniques with heavy timber and cross-laminated timber panels are ideal for mid-rise buildings, and high rise buildings up to 30 storeys. I wanted to research more into using timber in cities. Canada particularly has a vast resource of responsibly harvested forests and can contribute to the diversity of building typology in cities like Toronto.

Identifying the material makeup of our cities helps shed light on the manufacturing infrastructure needed to continue to build and to increase density. Comparing the existing dominant materials—concrete, steel, and timber—can shape the future, managing material resources and energy in our ever growing cities.



Fig. 0.1 Downtown Toronto construction boom, 2008. Photo by Jim Crocker.

Fig. 0.2 (Facing top) 10-storey mixed-use CLT development proposal in London by Hawkins Brown Architects.

Fig. 0.3 (Facing bottom) *ibid*

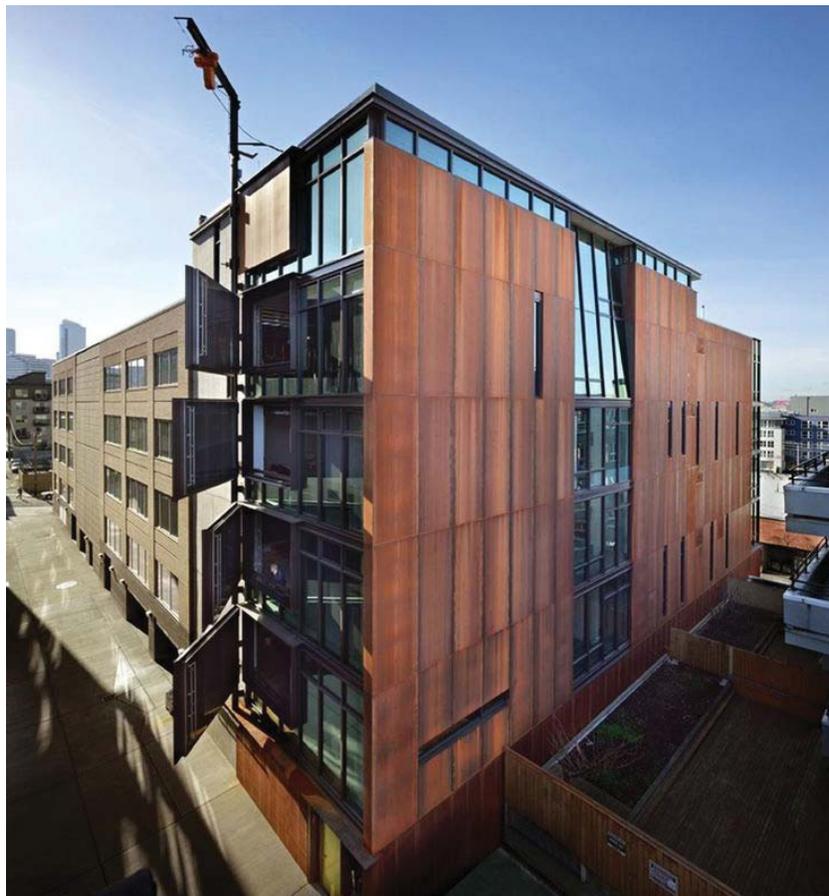
Fig. 0.4 (Following top left) Art Stable urban infill residential project in Seattle using steel framing by Olson Kundig Architects.

Fig. 0.5 (Following bottom-left) *ibid*.

Fig. 0.6 (Following top right) adAPT New York City 'My Micro Apartment' by nARCHITECTS.

Fig. 0.7 (Following top left) *ibid*.







Guidelines

Toronto's metropolitan area population has increased by one-hundred thousand people each year from 2009 to 2012. With an almost 2.8 million person urban core, it is currently the fourth largest city in North America.¹ With this increase comes a demand for adequate housing and, in turn, more commercial buildings. These days, simply walking around the city, you can't help but notice the construction boom—shiny new condo towers, scaffolding, and cranes constantly going up, concrete trucks coming in and out of the city, and floor after floor rising each day.

For anyone involved in the building industry—architects, contractors, developers and consultants—the recent boom has been great for business. However, when we erect buildings at a feverish pace, we have to ask, how can we improve our current design and construction methods to create a healthier and more livable city? How can we implement change to the building materials that dominate the industry in order to use more energy-efficient materials and construction practices?

The answer lies in Toronto's backyard. Ontario contains a vast resource of responsibly-harvested forest regions as well as protected crown land. The wood industry here is known for making standard dimensioned lumber, mostly for light frame suburban housing, but it can be used to produce cross-laminated timber, which can be used to construct high performance buildings.

Cross-laminated timber panels are lumber boards, like 2x4's and 2x6's, that are laid out and glued in one direction, with alternating perpendicular layers glued on top to form a solid mass. This type of engineered wood provides architects with custom design flexibility, developing new geometry and open interior spaces, while using an inherently local renewable resource.

The building industry in Ontario has spent years pressuring the provincial government to adopt building codes similar to those

¹ "Population of Census Metropolitan Area," last modified February 02, 2006, <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/demo05a-eng.htm>.

Fig. 0.8 (Facing) View of Downtown Toronto construction. Photo by Torstar News Service.





Fig. 0.9 Three and five layer CLT panels.
Photo by unknown.

Fig. 0.10 (Facing top) CLT Structurlam plant
in Okanagan Falls, BC. Photo by Structurlam
Products Ltd.

Fig. 0.11 (Facing bottom) CLT Structurlam
panel assembly. Photo by Structurlam
Products Ltd.



in British Columbia, allowing six storey wood frame buildings, especially in urban areas. The Government of Ontario recently announced plans to change its current building codes to allow this height increase.² The ultimate test now will be to convince developers and architects that cross-laminated timber is worth the investment.

Although North America is slow using solid timber in construction, Europeans, most notably in England, Austria, and Germany, have built a wide range of projects, from mid-rise residential buildings to libraries and university buildings. Thorough testing has been conducted for fire rating, structural loads, and effect of seismic factors, in order to be included in many European building codes.³ These tests pave the way for British Columbia, and now Ontario, to use cross-laminated timber and heavy timber in the construction industry.

Using cross-laminated timber on infill sites in Toronto and in similar urban areas, brings energy-efficient and renewable materials to our cities, and alters the way we design and construct buildings. This thesis addresses four main guidelines, creating an in-depth perspective of cross-laminated timber. The material and its use is compared to steel and concrete in order to establish context in relation to the current structural materials used in cities. Cross-laminated timber has a huge impact in the design and construction industries, but there need to be key building projects in Toronto in order for change to occur.

In this document there are many different resources I looked at. The primary references on cross-laminated timber come from the Canadian edition of the *Cross-laminated Timber Handbook* by *FPIInnovations*, and current articles and information from the *WoodWorks* website. I referred to *Statistics Canada* and *Environmental Protection Agency* sites for current research on building materials and greenhouse gas emissions. Building construction processes are referenced from *Constructing Architecture: Materials Processes Structures - A Handbook*.

2 "Potential Building Code Amendments for Mid-Rise Wood Frame Buildings up to Six Storeys," last modified March 20, 2014, <http://www.ontariocanada.com/registry/showAttachment.do?postingId=15462&attachme ntId=23991>.

3 Gagnon and Pirvu, eds. *Cross-Laminated Timber Handbook*, ch. 1.

Fig. 0.12 (Facing top) Eight-storey residential CLT building, Bridport House in London by Karakusevic Carson Architects. **Fig. 0.13** (Facing bottom) structural 3D model, CLT supplied by Stora Enso. Photo by Stora Enso Building Solutions.



The guidelines diagram on the facing page is intended to form a discussion on each subject—*Environmental Performance, Ease of Manufacture, Organized Assembly, and Design Flexibility*. The three colours representing cross laminated timber, concrete, and steel, are rated against each other from weak to strong, in order to create this discussion. Rather than identifying the individual rating for each material, the highlighted regions provide an overall idea of where they land on the chart. The aim is to start a dialogue on how we manufacture and design with these three building materials.

The guidelines are introduced below:

1. Environmental Performance

There are two principle factors when analyzing a building material's environmental impact. The first involves material's embodied energy: how the raw material compound is extracted from the earth, manufactured and fabricated into a specific form, and transported and erected at the given site. The second is how the material performs over a period of time, its durability and lifespan, and the material's impact during a building's operational energy use. Measuring the environmental impact of our building materials, helps to account and manage energy use in buildings, cities, and more broadly, the ecological footprint: a measure of human consumption in contrast to earth's ability to sustain or regenerate natural resources.⁴

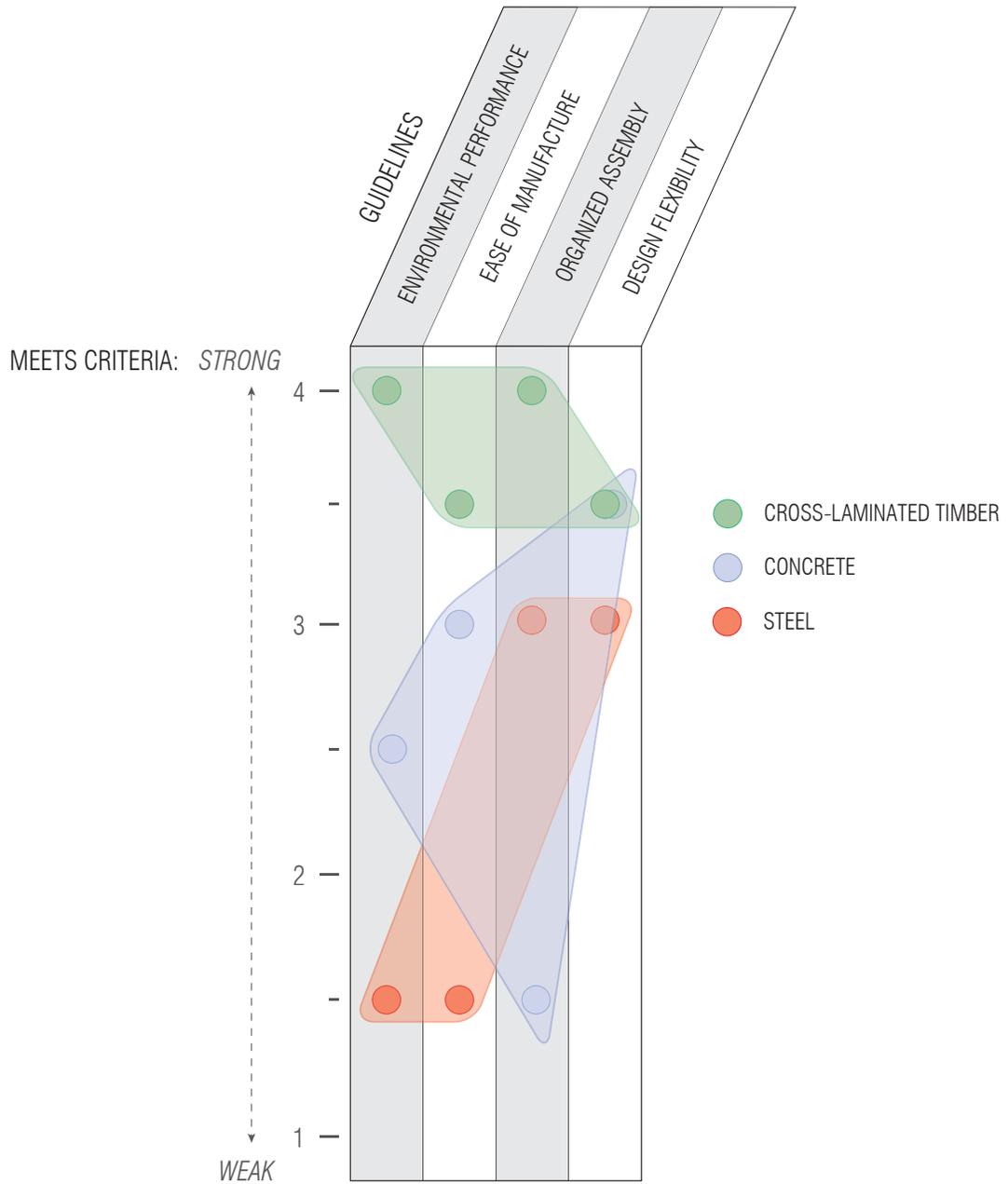
When it comes to overall environmental performance, compared to steel, concrete, and standard wood framing, cross-laminated timber is by far the best material. Cross-laminated timber is a natural, renewable material, harvested in certified forests. The timber panels are manufactured in safe facilities with very little waste, and increase the thermal performance throughout a building's lifespan.

2. Ease of Manufacture

Architects want to know the material supplier on a project can produce the components for their design on time and on

⁴ Wackernagel, *Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability* (PhD Thesis), 62.

Fig. 0.14 (Facing) Material guideline rating chart. Drawing by Author.



budget with high quality craft and precision. As the architecture and construction industry moves towards a digital standard workflow with Building Information Modeling (BIM) and an integrated design process, the need for collaboration between the architect and manufacturers is important to the overall success of the project. Cross-laminated timber has a highly-controlled manufacturing process, ensuring every detail is taken into account. The lumber boards are milled from early-growth certified forested regions with wood species based on where the manufacturing plant is located. The typical softwood species used are Spruce, Pine, and Fir. This section gives an inside look into the raw-material-to-product-production of cross-laminated timber, contrasting concrete and steel methods.

3. Organized Assembly

Every building project has to deal with on-site assembly methods. The specific climate conditions and time frame are key issues in the execution and success of the design. Building construction sites can be chaotic and unorganized, with multiple sub-contractors and tradesman trying to finish their jobs. This can lead to mistakes. Lawsuits are extremely detrimental for all parties involved but are a last resort in keeping everyone accountable. The more organized the on-site construction and assembly methods, the less likely there will be mistakes, disputes, and compromises, leading ultimately to a better end result for the users. Cross-laminated timber panels offer easily planned and precise construction assembly, shortening the assembly time, especially in colder climates.

4. Design Flexibility

Design flexibility encompasses essential factors in design. A client may introduce a number of different priorities for their project, depending on necessity and personal objectives. These priorities generally include, at minimum, durability, lifespan, aesthetics, and cost. A material should be able to accommodate and adapt to these qualities. Arguably, concrete, and steel can provide great design flexibility, but under specific constraints, site conditions, budget, program, assembly schedule, design

flexibility can become less important. Cross-laminated timber is a material that is a highly adaptable and flexible construction assembly system. This section discusses the historical development of the three materials, and their design strengths and weaknesses.

This describes a framework, showing how materials relate to design and construction. Guidelines give a direction and a strategy. In each section I will demonstrate how cross-laminated timber can compete with concrete and steel in North American urban centers, such as Toronto, where this thesis references a specific urban context. We are in the most ideal time and place to transform design and construction. It is an ethical responsibility for architecture, as an industry and a service to humanity, to provide better alternatives to the status-quo.

“Architecture finds itself in a similar predicament, as speculation and the machine have taken it over in the same way that they have subdued the technical arts. The architect is often little more than an inconsequential adviser in materials of taste and can expect neither esteem nor profit from his commissions.”

- Gottfried Semper, *Style in the Technical and Tectonic Arts; or, Practical Aesthetics*, 1862. 76.

“The design of how we go about designing, and ultimately making, circumscribes what we make. It controls the art found in its quality, scope, or features and also the resources of time and money expended on its production. This reality is completely contrary to the artistic and contractual structure of much current architecture, which specifically excludes the architect from participation in the “means and methods” of making, thus turning architects into mere stylists.”

- Kieran/Timberlake, *Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction*, 2004. 7.

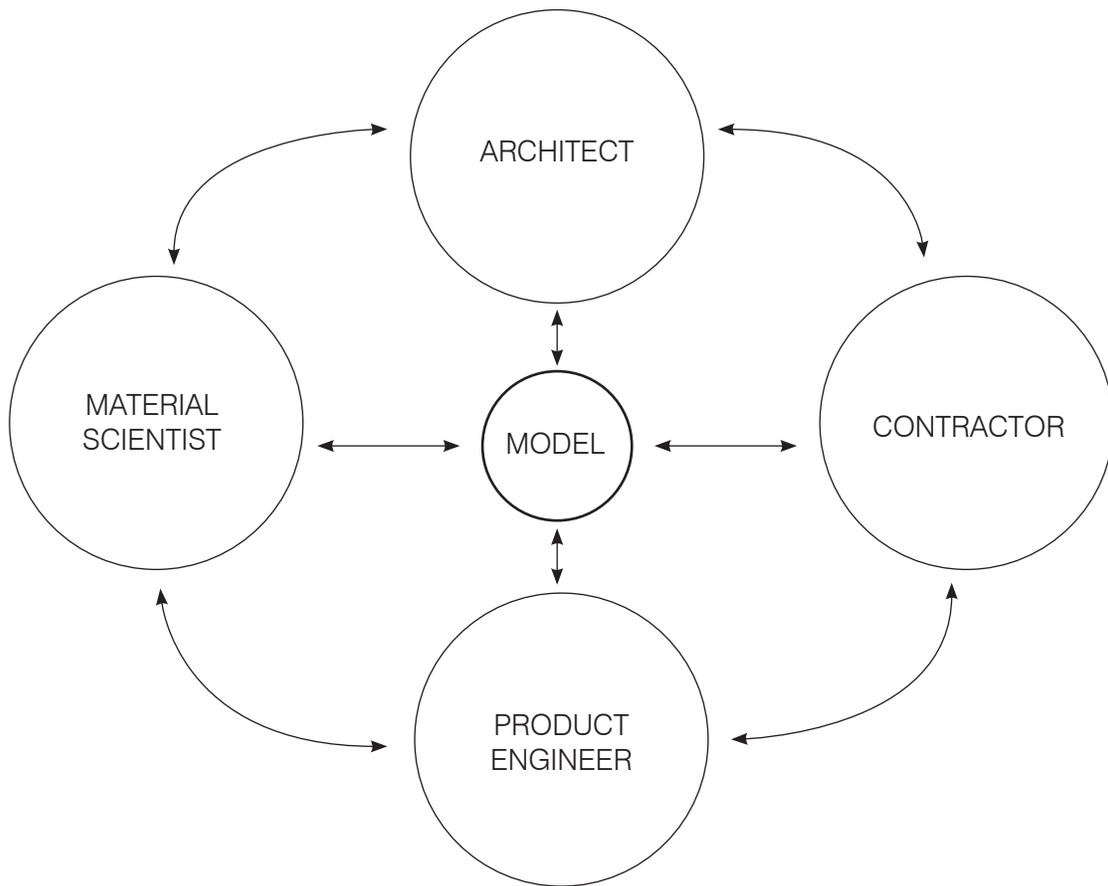
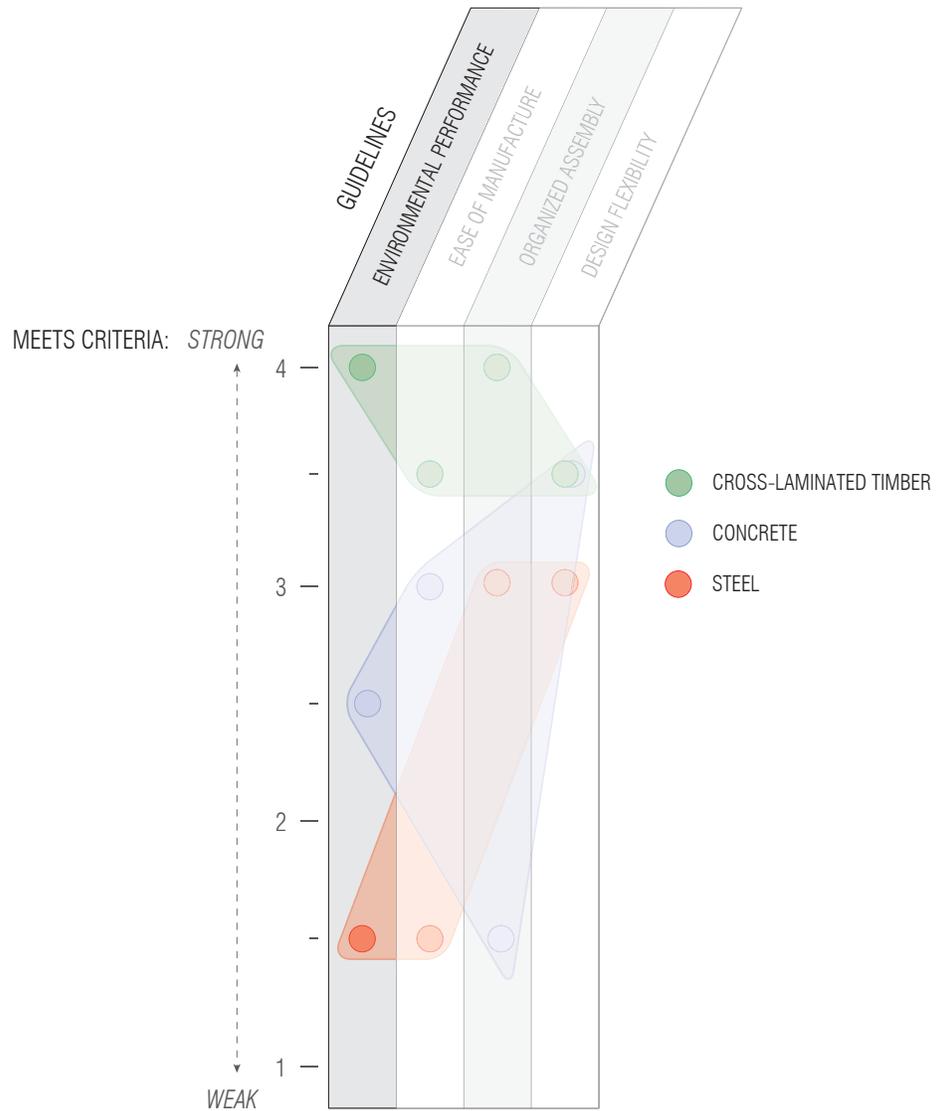


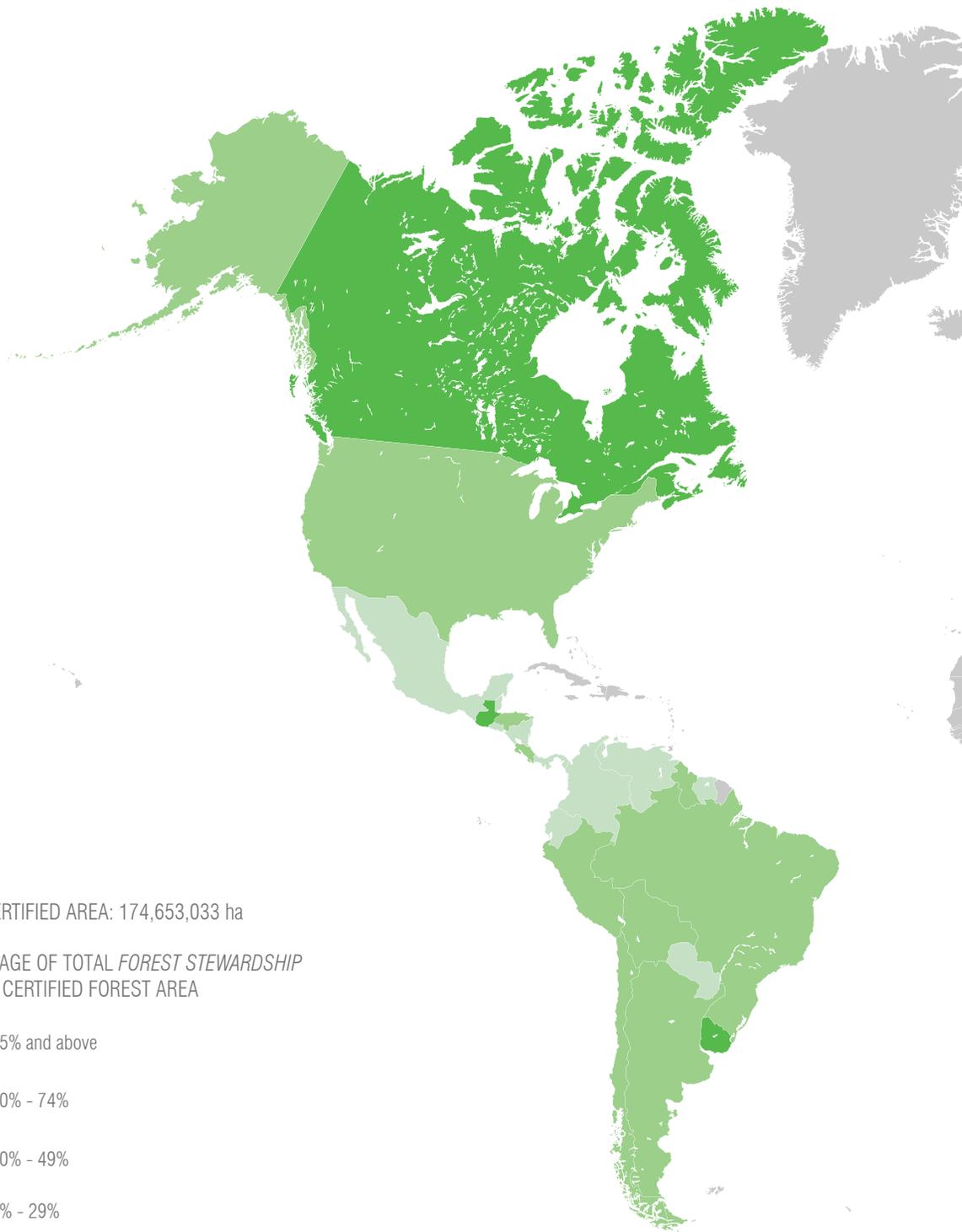
Fig. 0.15 Collective Intelligence design approach diagram by Kieran Timberlake Architects. Modified by author.



1.0 Environmental Performance

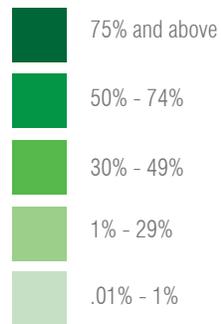
Rating: Cross-laminated timber 4/4. Concrete 2.5/4. Steel 1.5/4

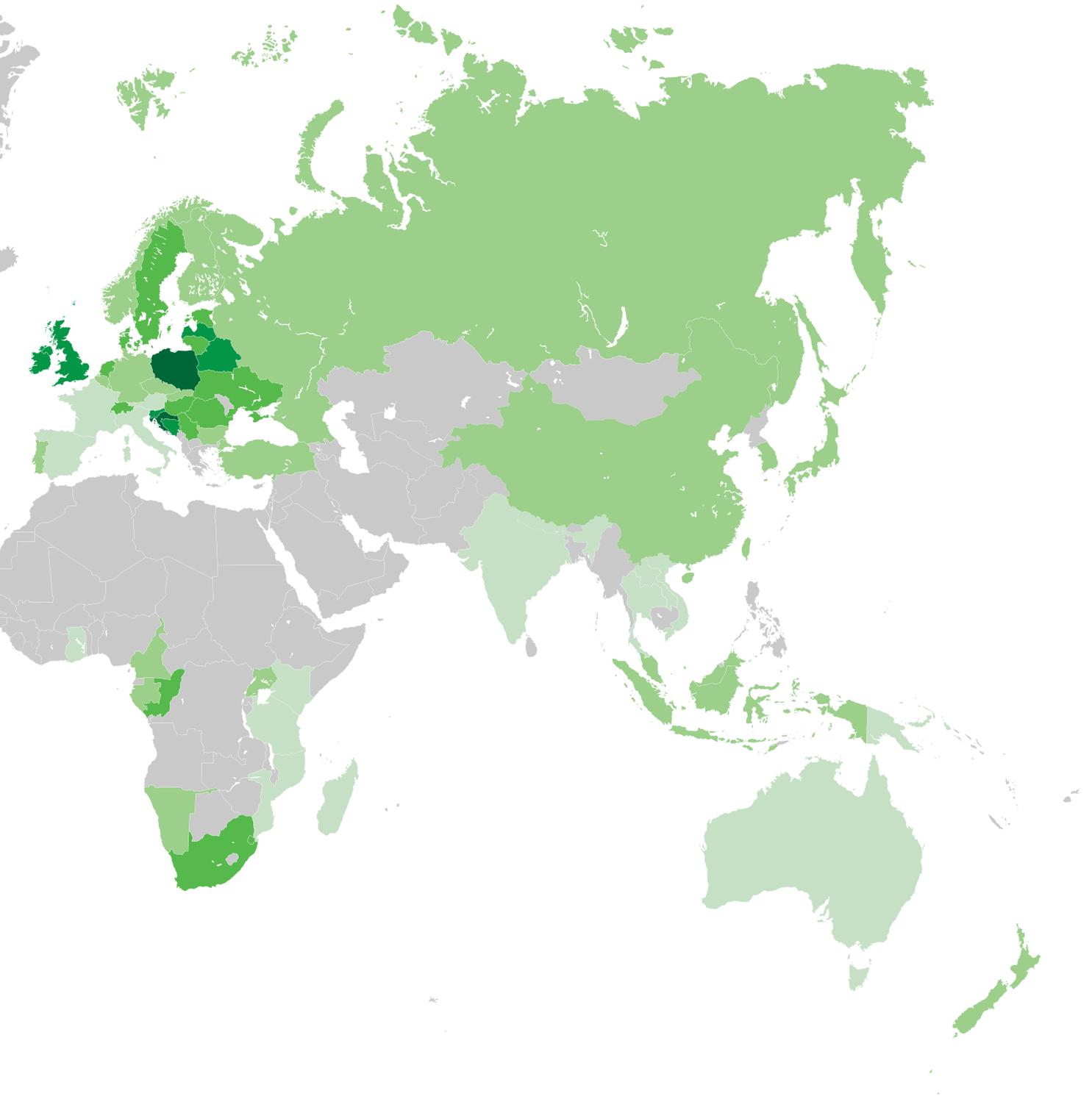
Cross-laminated timber ranks highest in Environmental Performance. Timber is a renewable resource, stores carbon, energy efficient to manufacture, and a great thermal insulator over a building's life-span. Concrete is accessible to manufacture around the world, but is energy intensive, and difficult to recycle. Steel can be recycled efficiently, but consumes the most energy out of the three materials to manufacture, and is a conductor, resulting in thermal bridging and poor thermal performance in buildings.



TOTAL CERTIFIED AREA: 174,653,033 ha

PERCENTAGE OF TOTAL *FOREST STEWARDSHIP COUNCIL* CERTIFIED FOREST AREA





Environmental Performance

Life Cycle Assessment is a assessment of the environmental performace and potential impacts associated with each stage of a product's life, from raw material extraction to demolition.¹ Life Cycle Assessment has increased in popularity; until recently, we did not take into account the consequences of how energy was allocated. Energy was relatively cheap and thought of as an everlasting resource. Major industries—automotive, construction, and electronic industries—are realizing the economic benefits in energy efficiency and waste management. Households and individuals are becoming more aware of energy responsibilities too, composting left-over food, recycling plastics, glass, and metals, and monitoring their heating bill. The incentives for both industry and individuals are twofold: improving profits or saving on their annual budget, and acknowledging a growing responsibility to protect the environment from climate change.²

When evaluating a building's life cycle, researchers measure the amount of energy used in each stage of the building process. The main stages (figure 1.2) that produce energy in the building process are:

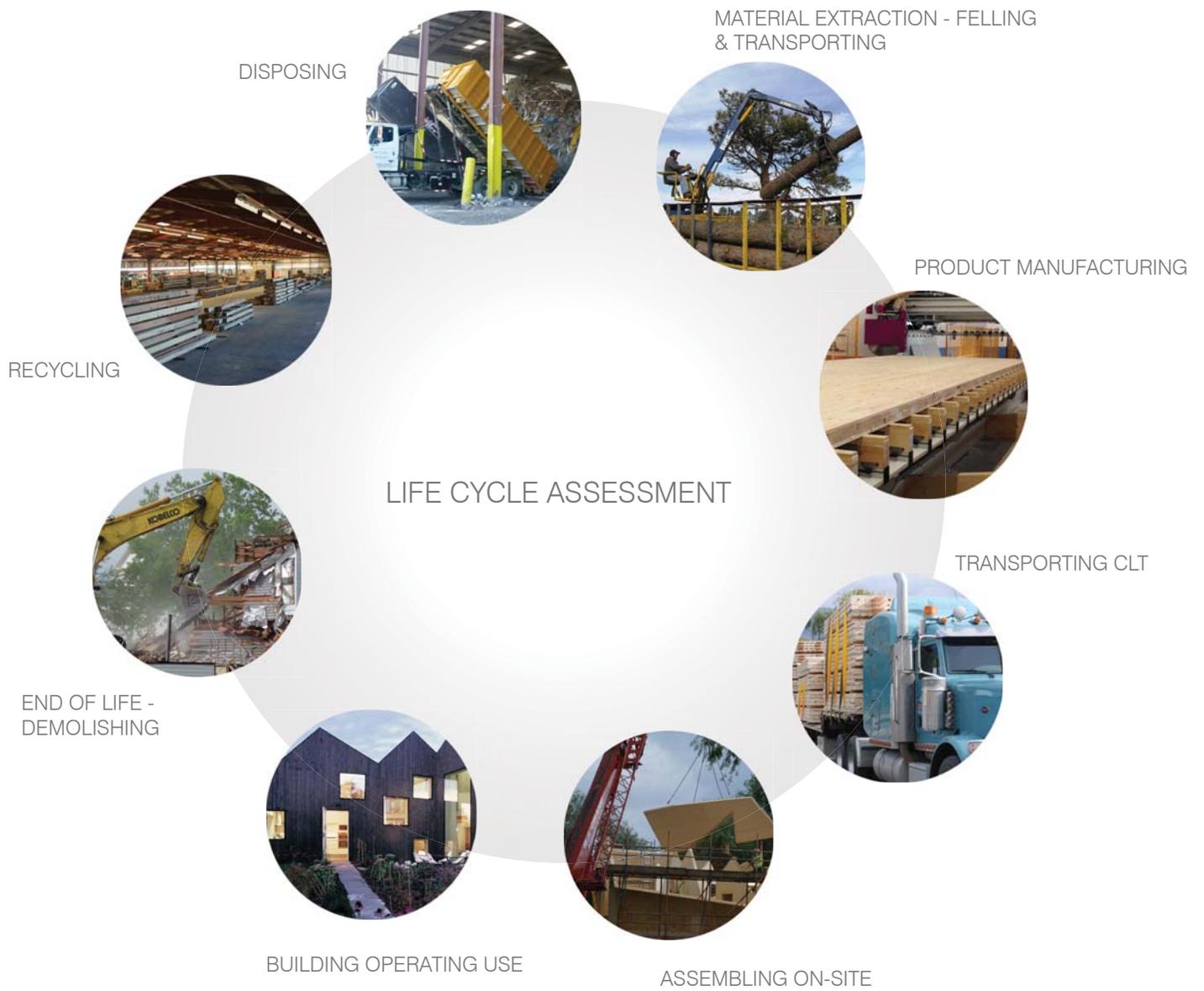
- Extracting raw materials, such as felling trees or mining limestone or iron ore
- Refining raw materials into usable goods
- Manufacturing material into final product
- Transporting products between each plant location
- Assembling materials on-site
- Consuming energy throughout the life of the building, such as heating and cooling systems, maintenance, and refurbishment
- Demolishing the building and transporting waste to disposal or recycling facility

It is difficult to track every product and determine a precise

1 "Life Cycle Assessment," last modified August, 2012, <http://www.epa.gov/nrmrl/std/lca/lca.html>.

2 Bribian, "Life Cycle Assessment of Building Materials: Comparative Analysis of Energy and Environmental Impacts and Evaluation of the Eco-Efficiency Improvement Potential," 1133.

Fig. 1.1 (Previous) FSC global certified area by country, 2013. (There are other forest certificates besides FSC). Diagram by author.
Fig. 1.2 (Facing) LCA diagram for CLT. Drawing by Author.



total energy use for a building as a whole. However, as product manufacturers and third party advocacy groups develop new tools for life cycle assessment, it is becoming easier to identify where energy can be saved. Because of these innovations, architects and clients can more easily make energy saving decisions for their projects.³

Cross-laminated timber, made from a natural renewable resource, is much more energy efficient than steel and concrete. Cross-laminated timber does produce some carbon dioxide during the manufacturing and transportation stages. However, almost all building products produce some carbon dioxide. The benefit of cross-laminated timber is that trees consume carbon during their growth, and once felled, trap carbon for their entire life cycle. Research studies in life cycle assessment account for a tree's ability to sequester carbon. The amount of carbon saved is far greater in comparison to petroleum-based materials like concrete, steel, and glass (figure 1.5).

The earth has finite resources. Therefore, the building industries must continuously innovate to find solutions. According to the U.S. Energy Information Administration, the building industry consumes 48.7% of all energy produced in the United States (figure 1.4). The manufacturing of supplies certainly contributes to energy consumption in the building industry. However, people less often think about the energy that goes into a buildings assembly and overall lifespan. For example, whether materials are assembled at the building site or fabricated prior to on-site work, may have a significant impact on the amount of energy expended over the buildings lifespan.⁴

Some environmentalists argue that using timber in buildings contributes to the problem of deforestation, making wood less environmentally friendly. This argument does have some merit. Unregulated forest areas, particularly in the tropical and subtropical regions are being irresponsibly harvested. However, the use of timber as a primary material in buildings does not necessarily result in deforestation if done properly. Europe, has led the way in responsible forestry. Europe contains

3 Spiegel and Meadows, *Green Building Materials: A Guide to Product Selection and Specification*, 6-7.

4 "Architecture 2030 Will Change the Way You Look at Buildings," last modified 2011, http://architecture2030.org/the_problem/buildings_problem_why.

Fig. 1.3 (Facing top) Global forest cover by millions of hectares. Diagram by Building Information Foundation, RTS.

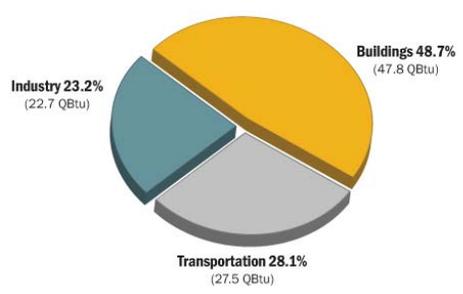
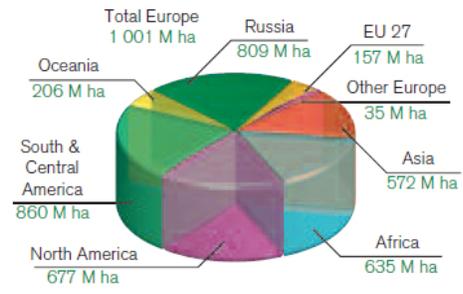
Fig. 1.4 (Facing middle) U.S. energy consumption by sector. Diagram by U.S. Energy Information Administration.

Fig. 1.5 (Facing bottom) Building material CO₂ production comparison. Diagram by Building Information Foundation, RTS.

Fig. 1.6 (Following left) Canadian forest and certified areas, 2013. Diagram by Certification Canada.

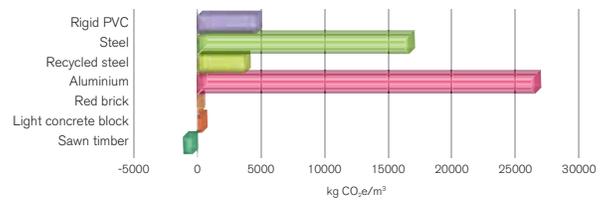
Fig. 1.7 (Following right) Forest certification types in Ontario, 2013. Diagram by Certification Canada.

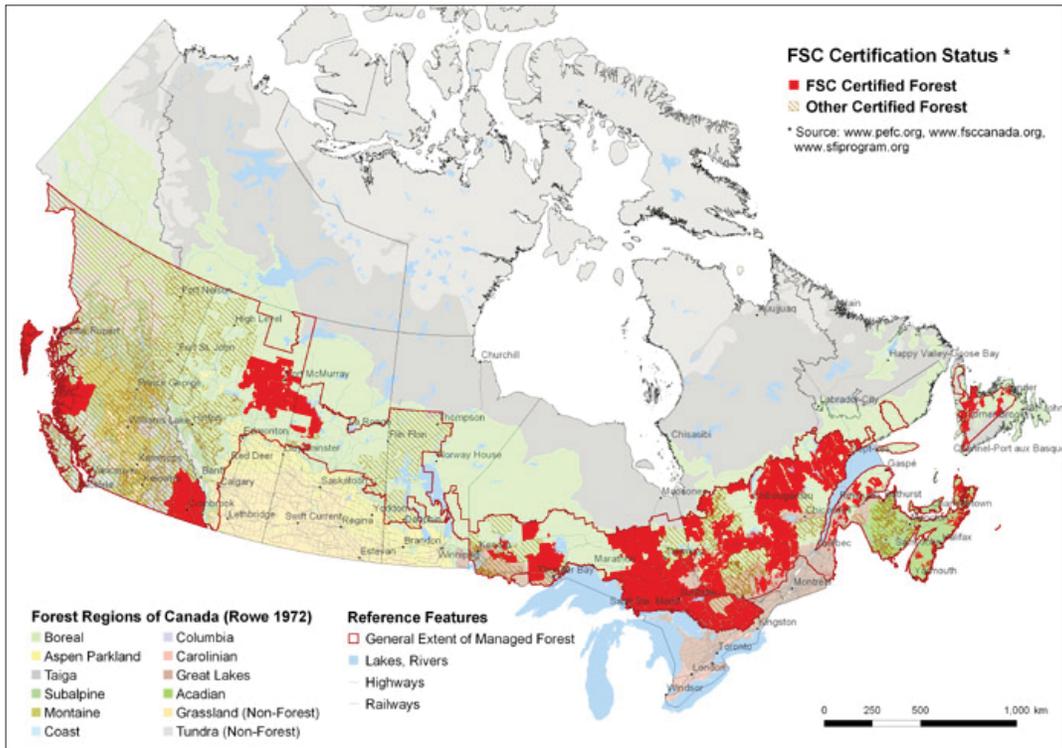
Global forest cover

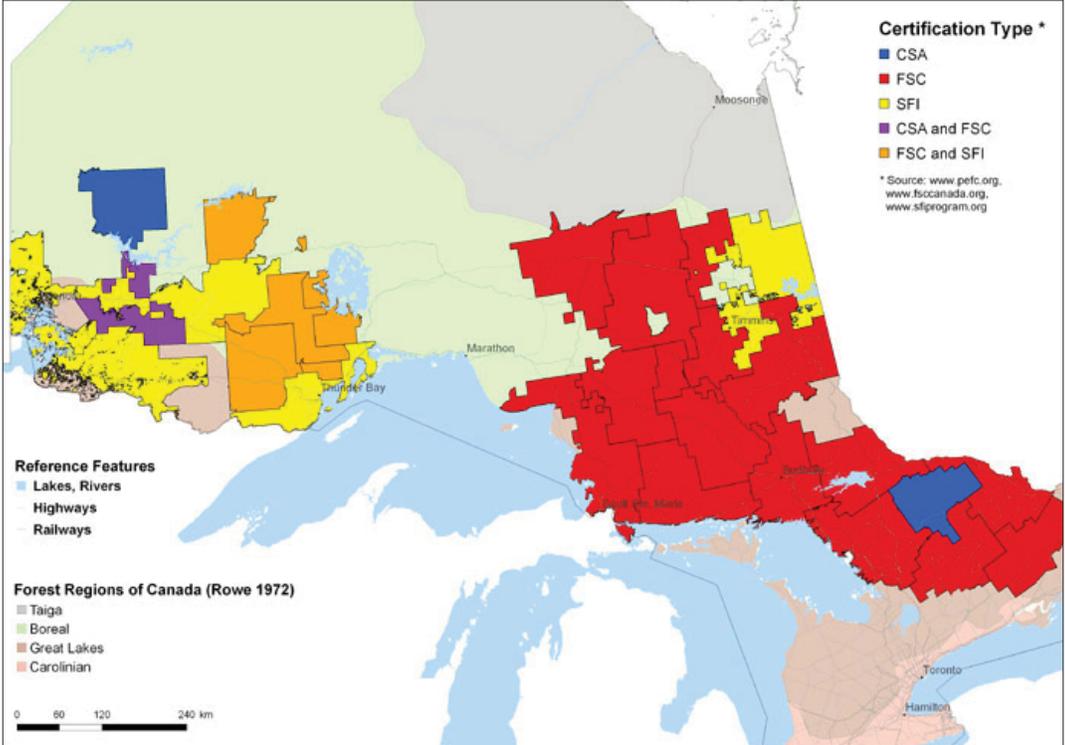


U.S. Energy Consumption by Sector
Source: ©2011 2030, Inc. / Architecture 2030. All Rights Reserved.
 Data Source: U.S. Energy Information Administration (2011)

Net emissions of CO₂ including carbon sink effect







only 5% of the overall global forests, but with responsible forest management, it produces 25% of world industrial forest products. On top of that, Europe's forests are increasing at an annual net rate of 661,000 hectares. Through responsible forest management, Europe has proven that timber does not have to cause deforestation, in fact it can be a regenerative natural resource.⁵

Compared to Europe, Ontario has a vast supply of monitored forests and is in line with European mandates for responsible forestry. 66% of Ontario is forested, a total of 71.1 million hectares. 52%, 56 million hectares, is productive forest. The actual managed forest area for harvesting as of 2009/2010 was 27.2 million hectares. 99,464 hectares were harvested in that year, a total of 10.6 million cubic meters of wood, which was a third of allowable harvesting for the year. 0.5% of total trees were harvested with three trees being planted for every one tree removed.⁶

These statistics help to show the magnitude of Ontario's timber resources, and the extent to which the government applies strict responsible management. Cross-laminated timber, a local renewable resource, can help to offset the need to use high-energy consuming steel and concrete in the building and infrastructure industry.

Responsible forest management is only one environmental factor. The cross-laminated timber manufacturing process is comparably energy efficient. The manufacturing process is quite dry—there is little water used to refine the raw material into the product. The wood does not need to be heated to high temperatures like concrete and steel. Cross-laminated timber uses heavy machinery in a well-established technology, to fell trees in difficult terrain and process the logs into boards. One drawback to timber manufacturing is the potentially high transportation costs, depending on where the final building site is located. However given Ontario's dimensional lumber production facilities, there is great potential for new CLT

5 Wegener, "Ecological Significance," in *Building with Timber: Paths Into The Future*, 16.

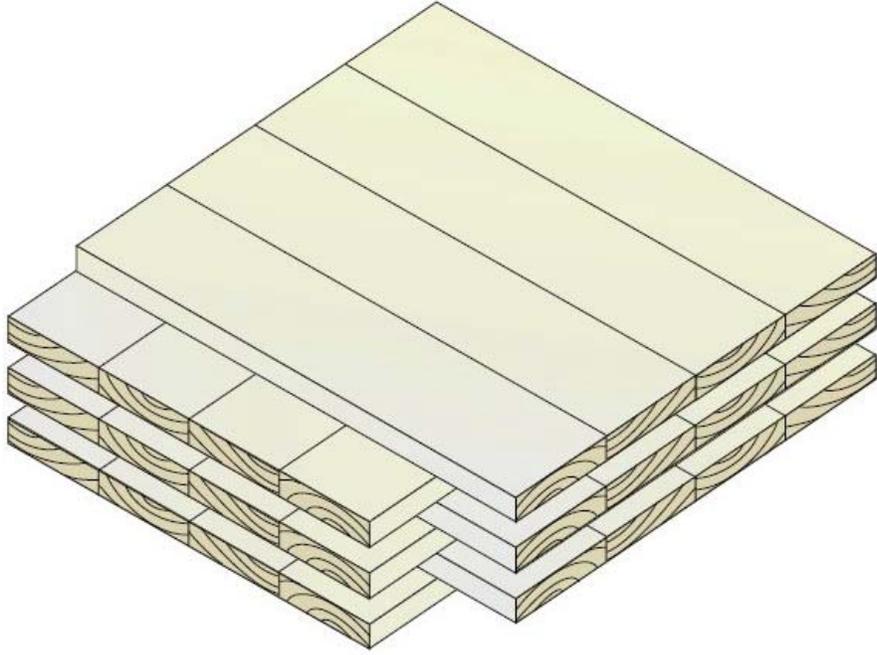
6 "Ontario's Forests," last modified February 27, 2013. http://www.mnr.gov.on.ca/en/Business/OntarioWood/2ColumnSubPage/STDU_139100.html.

Fig. 1.8 (Facing top) Cross-laminated timber panel configuration. Diagram by FPInnovations.

Fig. 1.9 (Facing bottom) Interlocking cross-laminated timber (ICLT) panels using trees killed by the mountain pine beetle in western North America. The method is being tested at the University of Utah. Photo by Joe Mayo.

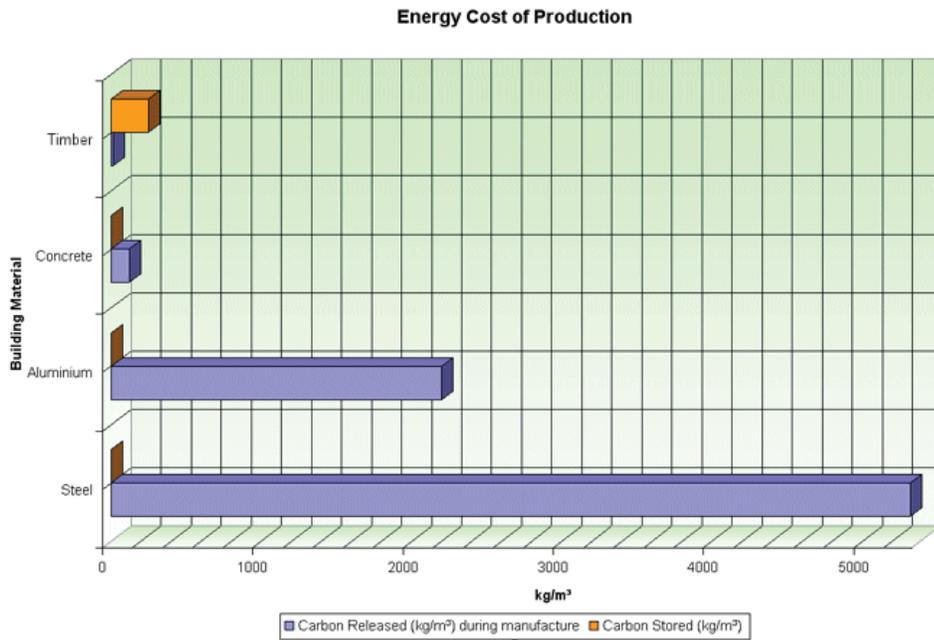
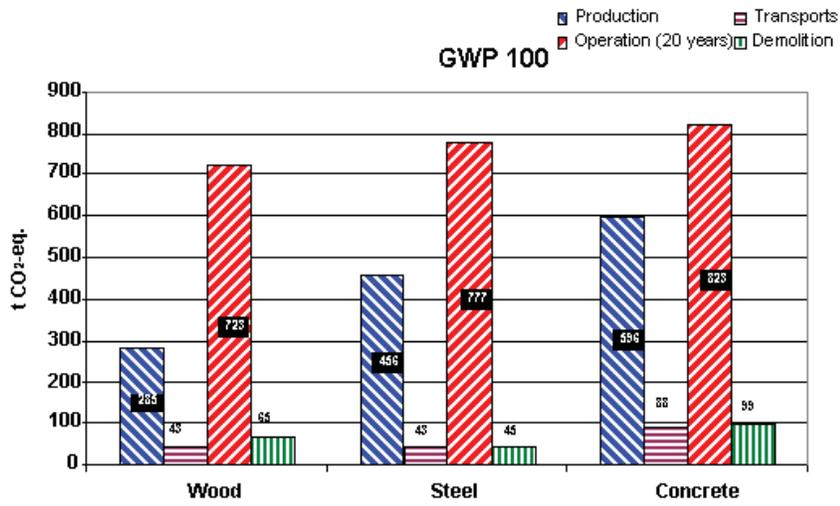
Fig. 1.10 (Following left) Ontario coniferous forest region, 2009. Photo by Paul Henman.

Fig. 1.11 (Following right) Building materials that can be produced for one ton of CO₂. Diagram by Materials Council UK.









manufacturing and fabrication initiatives.⁷

Cross-laminated timber manufacturing stages include: felling, debarking, plain or quarter sawing into boards, planing, laying up the panels, gluing, and pressing (figure 2.4). This production system is relatively straightforward and less energy intensive than concrete and steel. Engineers and manufacturers are implementing new systems to increase energy efficiency. For example, manufacturers have begun using scrap wood cutoffs and sawdust produced during the milling process for biofuels and insulation, allowing 90% of each log to be used. Concrete and steel manufacturers are finding ways to save energy as well, but even with these new innovations, many stages are inherently exhaustive. I elaborate more in the next section, *Ease of Manufacture*.

Another factor in environmental performance to assess is a building's operational energy. Operational Energy Use is the amount of energy a building consumes while in productive use. Whether a building is composed primarily of concrete, steel, or timber significantly effects its operational energy use. Cross-laminated timber performs as an excellent thermal insulator; heat moves slowly through wood.

Wood is a poor conductor, while metals maintain the highest conductive properties. In order to quantify heat transmission and thermal insulation, materials are measured using three factors: (1) K-value—how good a material performs as a thermal conductor. The lower the K-value, the better the materials thermal performance. (2) U-value—how much heat is lost based on a specific materials thickness. The lower the U-value, the better the material is able to insulate heat. And (3) R-value—the resistance to heat flow through a material. The greater the R-value, the better the material performs as a thermal insulator.

Cross-laminated timber has an R-value of 1.25 per inch. Concrete and structural steel perform much lower. Concrete's R-value is 0.1 to 0.2 per inch and steel is 0.003 per inch,

Fig. 1.12 (Facing top) Wood, steel, and concrete LCA CO₂ emissions chart. Diagram by FAO.

Fig. 1.13 (Facing bottom) Energy cost during material production. Diagram by unknown author.

⁷ "The Canadian Lumber Industry: Recent Trends," last modified November, 2009, <http://www.statcan.gc.ca/pub/11-621-m/11-621-m2007055-eng.htm>.

“The introduction of sustainability concerns requires that individual designers take into consideration complex issues such as maintenance, repair, and recycling. It requires the complete integration of energy conservation, emissions reduction, and many other aspects. This cannot be achieved through traditional sequential design processes; instead, integrated and interdisciplinary design must become the new standard.”

- Werner Sobek, *Architecture Isn't Here to Stay: Toward a Reversibility of Construction*, 2010. 36.

respectively. In terms of conductivity—K-value—typical softwood lumber ranges from 0.7 to 0.10 Btu (British Thermal Unit) per inch. In comparison steel is 310 Btu, and concrete is 6 Btu. Glass has a K-value of 7 while an insulation material like mineral wool is 0.25 Btu per inch.⁸

These measurements provide an idea of some of the common materials used in buildings and how they relate to energy efficiency. The material's thermal properties contribute to risk of thermal bridging. In thermal bridging, heat moves through the path of least thermal resistance. For example, thermal bridging is common in colder climates, where buildings have concrete or steel penetrating through the envelope, such as balconies or overhangs. Heat moves from the warmer interior through the material to the colder exterior, creating increases in the overall building energy costs. Energy loss also works in the reverse environment where interior air conditioning is lost through materials to the exterior.

Timber's thermal properties lower the risk of thermal bridging. Air leaks are less likely to occur in cross-laminated timber buildings because precise CNC (Computer Numerical Control) machining ensures tight fitting joints and connections. Window and door fittings may take place off-site in cross-laminated timber facilities, helping to lower a buildings energy costs.⁹

The recycling process at the building's end of life has been improving for all three materials. Steel is the most valuable material for recycling because it saves a considerable amount of raw iron ore material. One ton of scrap metal saves approximately 2,500 pounds of iron ore, 1,400 pounds of coal, and 120 pounds or limestone from being mined. Concrete can be recycled as well, but involves crushing large chunks of concrete, separating the steel rebar, and crushing the residue into smaller aggregates to produce a new batch mixture.¹⁰ While recycling concrete and steel is beneficial for conservation and energy, both still involve

8 Gagnon and Pirvu, eds. *Cross-Laminated Timber Handbook*, 11.

9 "Cross Laminated Timber (CLT)," last modified 2014, <http://woodworks.org/design-with-wood/building-systems-clt/>.

10 Materials Matter, *Architectural Record*, March 2011, McGraw-Hill Construction, <http://continuingeducation.construction.com/article.php?L=221&C=754&P=1>

substantial investments and energy consumption. Older timber posts and beams can also be recycled and are valued for their dry material behaviour, when the wood is less likely to split and shrink.¹¹ Cross-laminated timber has not been around long enough for end-of-life recycling systems to take effect, but if buildings are mindfully dis-assembled, the timber panels can easily be recycled or repurposed for other buildings.

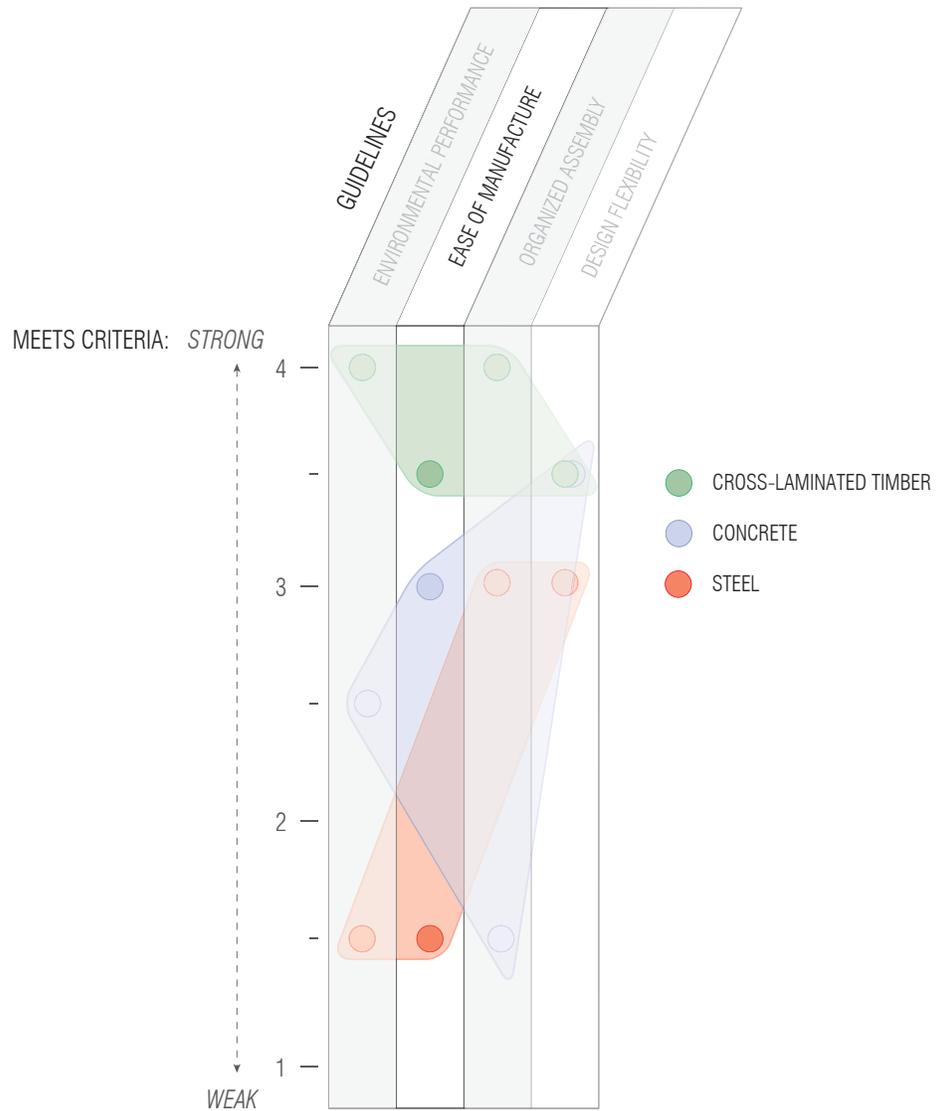
Environmental performance in architecture is an ever-evolving issue. We must implement new solutions. In buildings, some solutions have already been adopted. Particularly mechanical devices such as photovoltaics, geothermal heat pumps, and gray water collectors are readily available within the architectural practice. Yet, shaping our basic building materials must also be part of the formula. Using cross-laminated timber to compete with the dominant structural materials, although a fairly small step, would be a major shift in how we choose and manufacture materials within our geographic realm.

The next section, *Ease of Manufacture*, defines each material process in-depth, expanding on processes mainly taken for granted in the built environment.

11 Kula and Ternaux, *Materiology*, 14, 44, 102.

“While the resources were considered part of the natural realm, the building was located in the cultural domain. Today, this dialectical relationship is undergoing a dramatic change, which becomes manifest in two major shifts...The material resources of construction are becoming increasingly exhausted at the place of their natural origins, while inversely accumulating within buildings. For example, today there is more copper to be found in buildings than in the earth. As mines become increasingly empty, our buildings become mines themselves.”

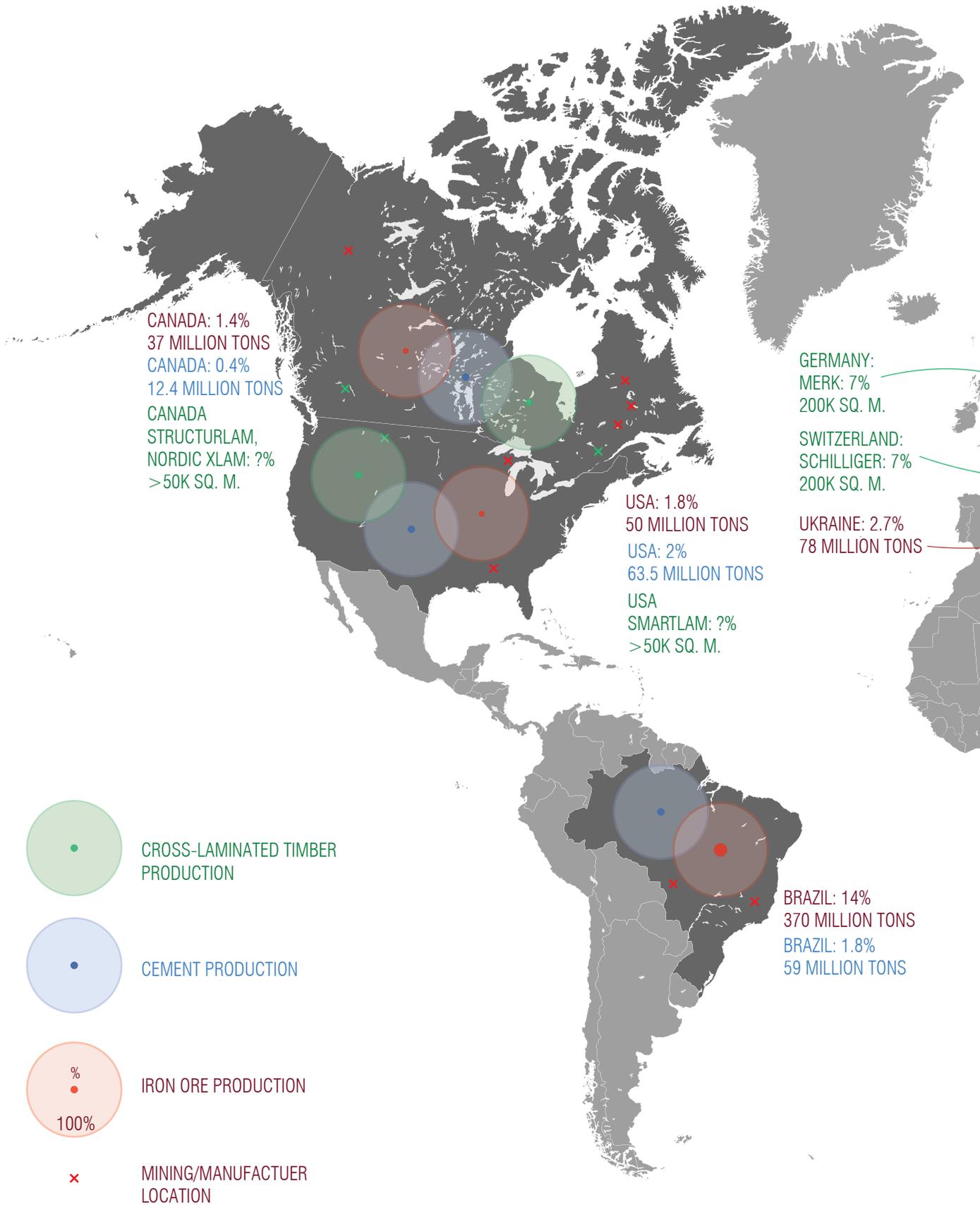
- Ilka and Andreas Ruby, *Re-inventing Construction*, 2010. 243.



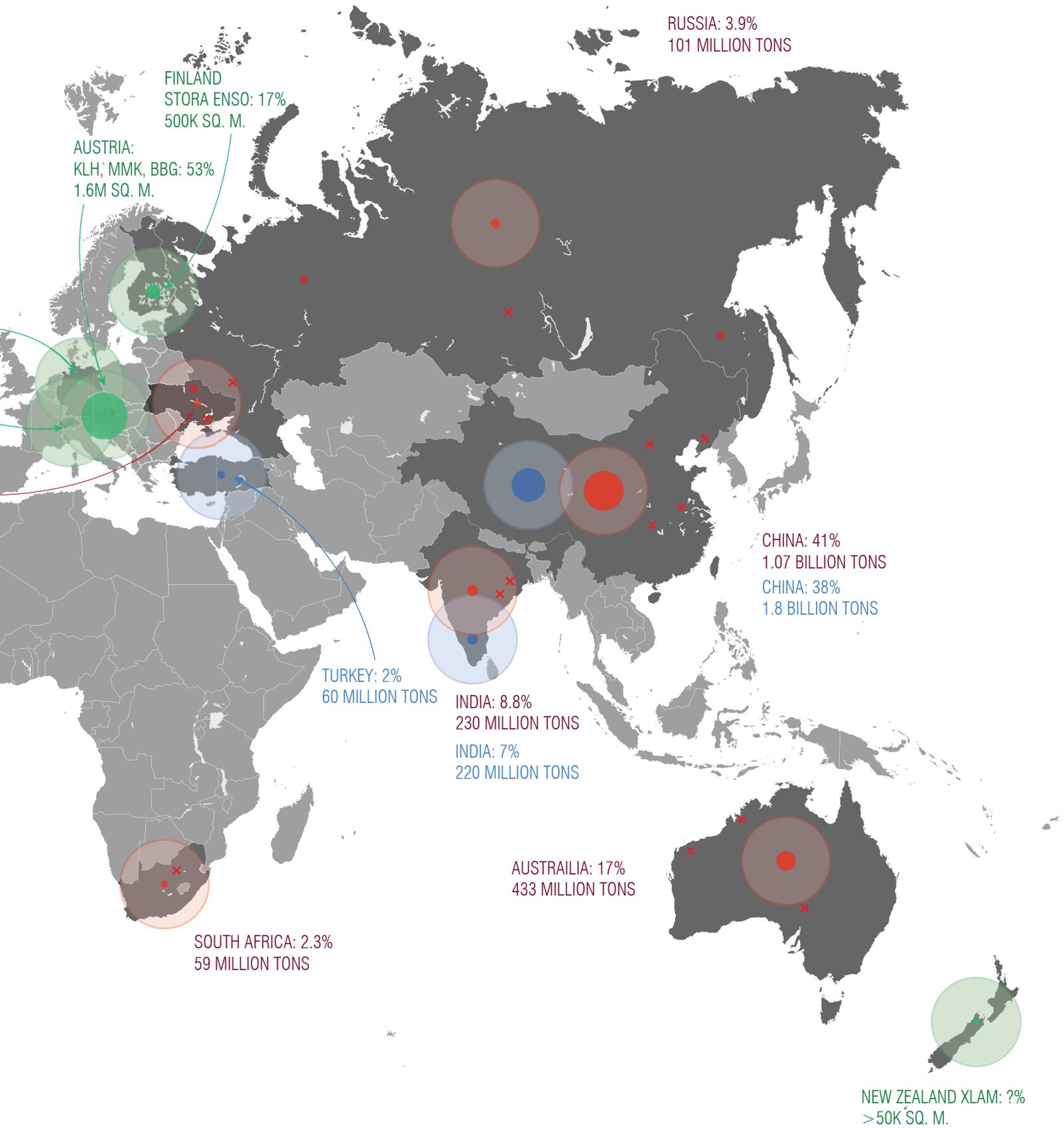
2.0 EASE OF MANUFACTURE

Rating: Cross-laminated timber 4/4 | Concrete 3/4 | Steel 1.5/4

Cross-laminated timber is made up of mostly Spruce-Pine-Fir trees, responsibly harvested in a growing number of countries. The manufacturing process is similar to that of standard lumber with the addition of adhesive and pressing machines to form the panels. Drawbacks include unfamiliarity with technical issues and their relation to local building codes. Concrete is relatively simple to manufacture, made of a mixture of limestone, sand, and water, but is energy intensive, using high temperature furnaces and water. Steel is the most energy intensive manufacturing process, made up of iron ore and coal, heated to high temperatures.



Data is approximate production for CLT, Cement, and Iron Ore in 2010



Ease of Manufacture

Cross-laminated timber achieves the highest rating for *Ease of Manufacture* compared to concrete and steel. This is primarily because the individual steps, from turning the raw material into a product, are less energy intensive. Factors for *Ease of Manufacture* include accessibility of the raw material, extraction of the material, machinery used to manufacture the product, and the actual processes involved in manufacturing, such as heating, cooling, and water consumption.

Using locally sourced timber from a certified forest contributes to lower transportation costs to the building site. A steel beam requires a tremendous amount of transportation of materials. In one example, iron ore is mined in China, the steel is manufactured in Belgium, and then shipped to Toronto for assembly. However, the harvesting, manufacturing, and assembly of cross-laminated timber can all take place in Ontario.¹ Using Toronto's city core as a major destination for construction, and the current northern Ontario lumber milling facilities as a potential source for manufacturing cross-laminated timber, will create a unique, regional building culture.

There are currently three manufacturers in North America producing cross-laminated timber panels: Nordic Engineered Wood in Quebec, Smartlam in Montana, and Structurlam in British Columbia. Some European manufacturers, seeing the potential in North America, have set up distribution locations. Some of the major manufacturers are KLH Massivholz based in Austria along with Mayr Melnof Holz and Binderholz Bausysteme GmbH, Stora Enso in Helsinki, Metsa Wood in Finland, Schilliger in Switzerland, and Merk Timber in Germany. New Zealand Xlam has also just started manufacturing timber panels.²

These producers use different species of trees depending on where the manufacturing plant is located. The ideal trees for manufacturing cross-laminated timber are a variation of spruce-pine-fir, douglas-fir-larch, and southern pine. These species, all

1 Ascher, *The Heights: Anatomy of a Skyscraper*, 76.

2 "Cross Laminated Timber (CLT)," last modified 2014, <http://woodworks.org/design-with-wood/building-systems-clt/>.

Fig. 2.1 (Previous) Annual production of cement, iron ore (tons) and CLT (sq. m) based on location of manufacturer and total percentage. Diagram by Author.

Fig. 2.2 (Following left) Log barge transport in Vancouver, 2006. Photo by Barnaby Dorfman.

Fig. 2.3 (Following right) Heavy timber processing plant. Photo by unknown.

being softwood (hardwood is primarily used for furniture), are abundant in controlled certified forest areas. They are fast growing, and are consistent in quality and grade.

The following describes the different stages to produce cross-laminated timber panels (figure 2.4).

First, a team of timber harvesters fells and stacks the logs for transportation. Trucks bring the logs to the mill for debarking, rotating the logs lengthwise against a sharp toothed machine, and bucking, cutting the logs to standard lengths. The logs are fed through vertical band saws and cut into boards. Standard dimensioned lumber uses the plain sawn method, which yields the least waste and most strength based on the grain direction. The lumber is moved to an enclosed area for drying.³ Cross-laminated timber mandates that the moisture content of the lumber used is 12%. Standard framing lumber is air dried to about a 20% moisture content. The boards are kiln dried, with air heated to 44-82° Celsius moving between the boards. This reduces swelling and shrinkage and ensures the adhesive used maintains its durability throughout the panel's life cycle. The dried boards are planed to specific dimensions and tested for strength, moisture content (once again), and defects. The boards are fed through an adhesive machine, which applies parallel lines of glue. Glue types vary in toxicity, but certain adhesives such as PUR adhesive, a formaldehyde-free and soluble adhesive, designed for high strength and durability, has been approved in many industrialized countries. For example the manufacturer KLH, in Germany uses PUR adhesive exclusively.

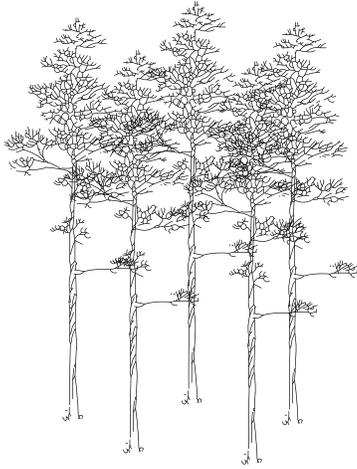
After glue is applied, the lumber is laid on the pressing bed in crisscross layers with the necessary panel dimensions.⁴ The boards are pressed into panels using either a vacuum press or a rigid hydraulic press. Cross-laminated timber press depends on how much load is required for the different panels. Hydraulic pressing is for larger loads and uses a pressure of 40-80 PSI (pounds per square inch), while vacuum pressing uses 14.5 PSI. The panels are moved to a sanding machine and cut to correct dimensions, then to a multi-axis CNC (computer numerically

3 Kula and Ternnaux, *Materiology*, 14.

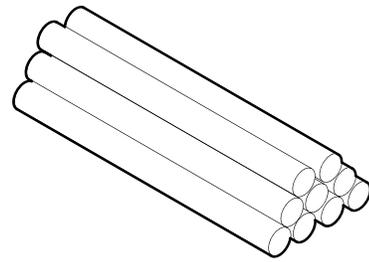
4 Deplazes, *Constructing Architecture: Materials Processes Structures - A Handbook*, 77.



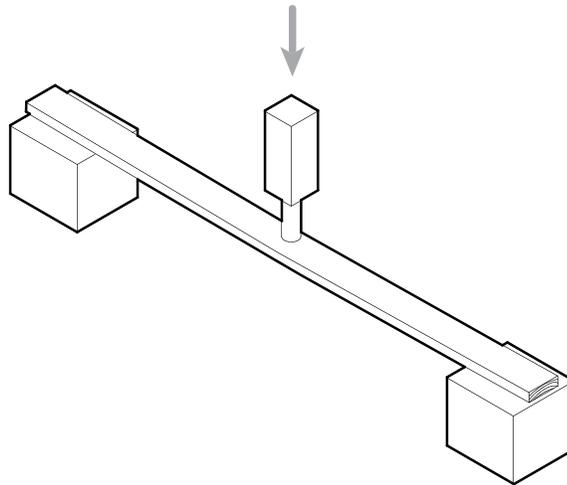




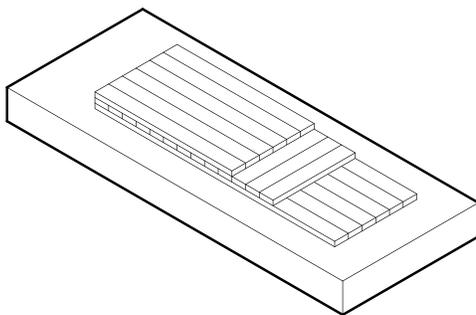
SPRUCE-PINE-FIR CERTIFIED FOREST



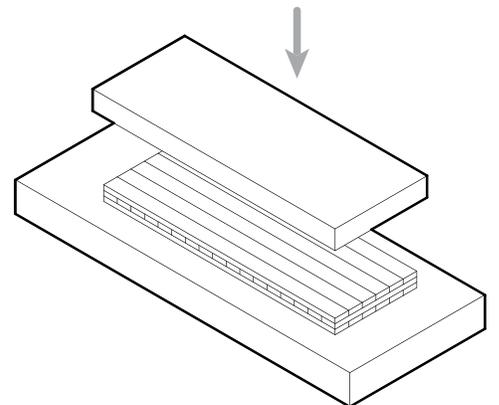
FELLING & LOG STACKING



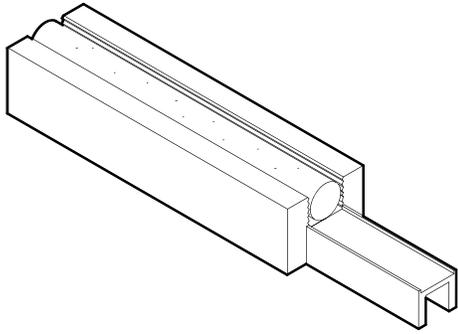
KILN DRYING, PLANING & STRENGTH TESTING



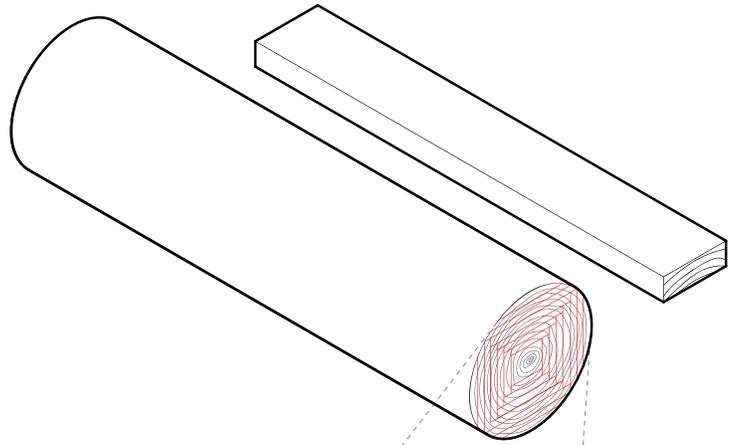
CROSS-LAMINATED TIMBER PANEL LAY-UP



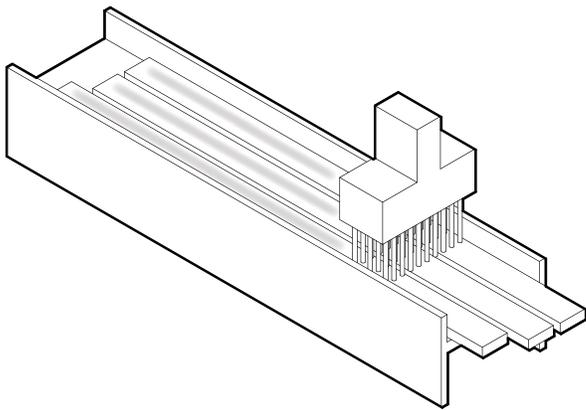
PANEL ASSEMBLY PRESSING



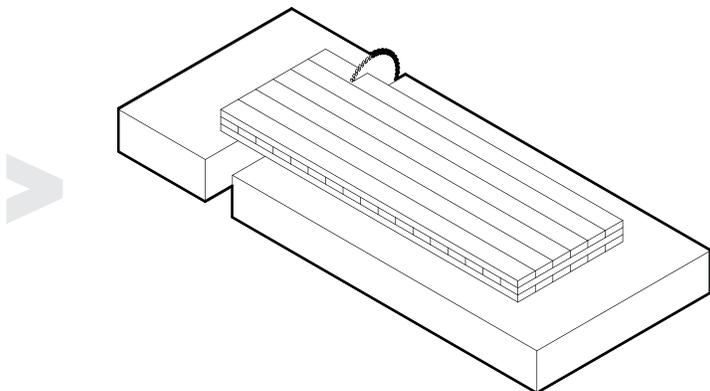
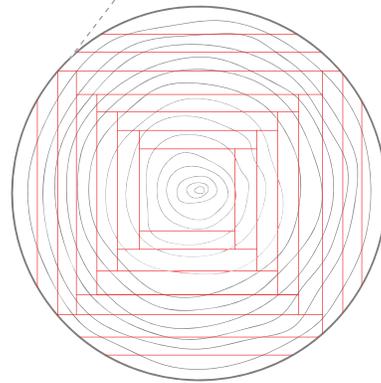
DEBARKING & BUCKING



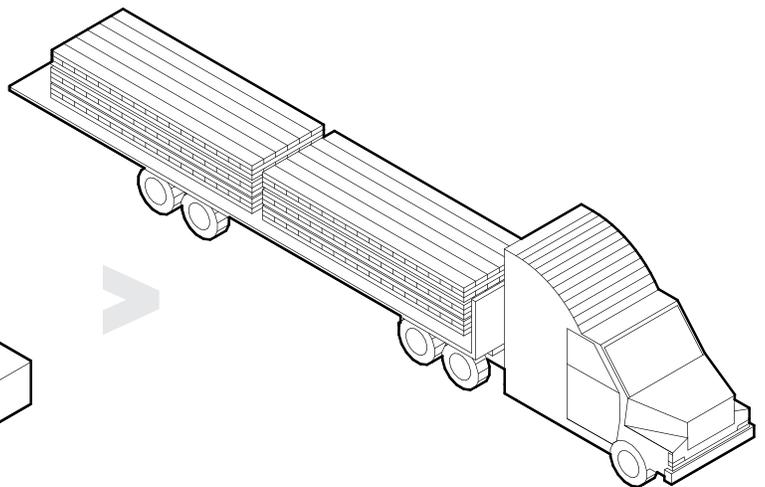
PLAIN SAWN LUMBER CUTTING INTO BOARDS



ADHESIVE APPLICATION



SURFACE SANDING & CNC CUTTING



CLT PANEL TRANSPORT



Fig. 2.4 (Previous) CLT production process. Diagram by author.

Fig. 2.5 Map of Chiboumamau to Toronto. Diagram by author.

Fig. 2.6 (Facing top) Aerial view of Chantiers Chibougamau timber facility in partnership with Nordic. Photo by Chantiers Chibougamau Ltd.

Fig. 2.7. (Facing bottom) Interior view of facility. Ibid.



controlled) machine where connection details, and door and window opening are routed out of the panel. Local compliance officials make sure the panels are up to par and sufficient for use in buildings. The panels are packaged and sent to the contractors and architects with information regarding wood species, panel sizes, connection assembly marks, and directions for loading. The panels are then transported to the site, most likely by truck or ship.⁵

Concrete manufacturing, although rated higher than steel on the *Ease of Manufacture* guidelines chart, is still more energy intensive and costly than cross-laminated timber. Concrete is a relatively straightforward combination of sand and aggregates, a binder (most commonly cement, a water based binder), and an admixture. The ratio of materials in standard concrete, which has a density of 2400-2550 kg/m³ is:

1. Aggregates: 60 to 70% (2000kg/m)
2. Cement: 7 to 15% (250-400kg/m)
3. Water: 6% (150 kg/m)

The manufacturing process starts with acquiring the raw materials for cement (figure 2.9). Portland cement is most commonly used for buildings, but others such as quick-set and pozzolanic are used, the main differences being slightly different mixtures and curing behaviours. First, a team extracts limestone and clay from a quarry. Limestone quarries can be found in many parts of the world. Mining and extraction can have a harsh impact on the surrounding landscape. For one ton of Portland cement, one and a half tons of limestone and clay are needed.⁶ The stone is crushed to about fist size rocks at the quarry and trucked to a roller mill where the rocks are fed into a primary crusher with other raw materials such as sand and aggregates (other materials like recycled concrete and bricks can be used), screened for fine grain consistency and fed through a secondary crusher (a vertical grinder), and screened once again. The rocks are now a fine dust and stockpiled to dry, then transported to a cement plant.⁷

5 Gagnon and Pirvu, eds. *Cross-Laminated Timber Handbook*, ch. 02.

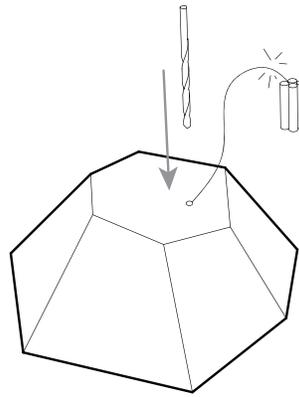
6 Bell and Buckley, *Solid States: Concrete in Transition*, 11.

7 Deplazes, *Constructing Architecture: Materials Processes Structures - A Handbook*, 60.

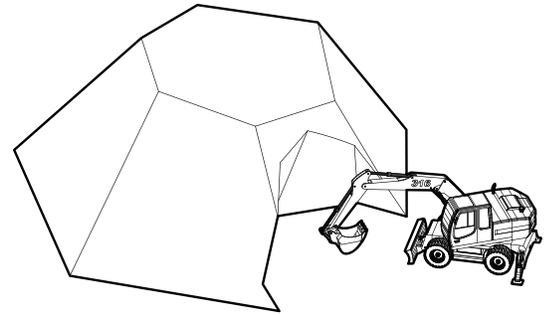
Fig. 2.8 (Facing) Limestone quarry in Japan from Lime Hills #22916, 1988. Photo by Naoya Katakeyama.

Fig. 2.9 (Following) Concrete manufacturing process. Diagram by author.

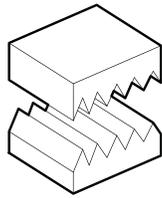




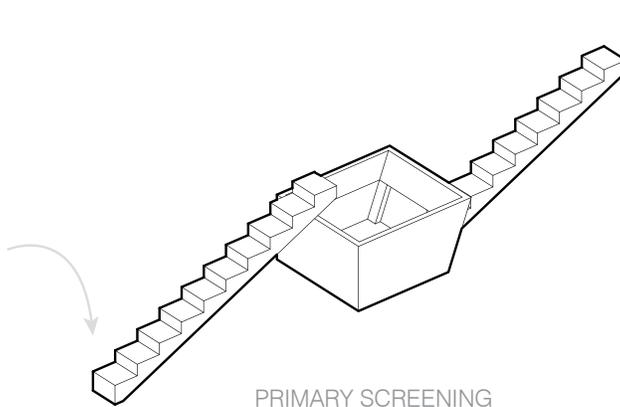
DRILLING & BLASTING LIMESTONE QUARRY



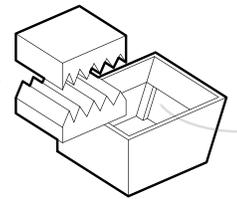
LIMESTONE & CLAY EXTRACTION



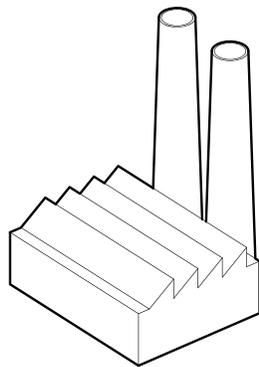
PRIMARY CRUSHER



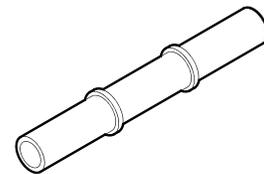
PRIMARY SCREENING



SECONDARY CRUSHER & SCREENING

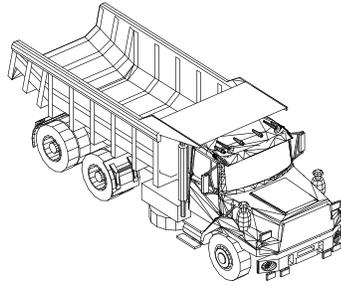


READY MIX CEMENT PLANT

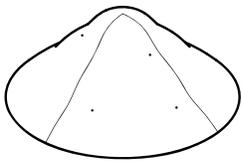


HEAT EXCHANGER, ROTARY KILN
AT 1000 - 1400 C.

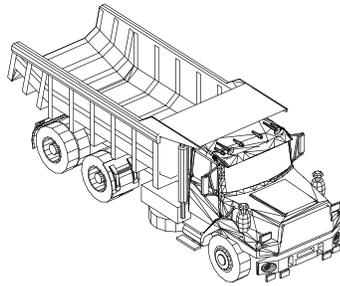




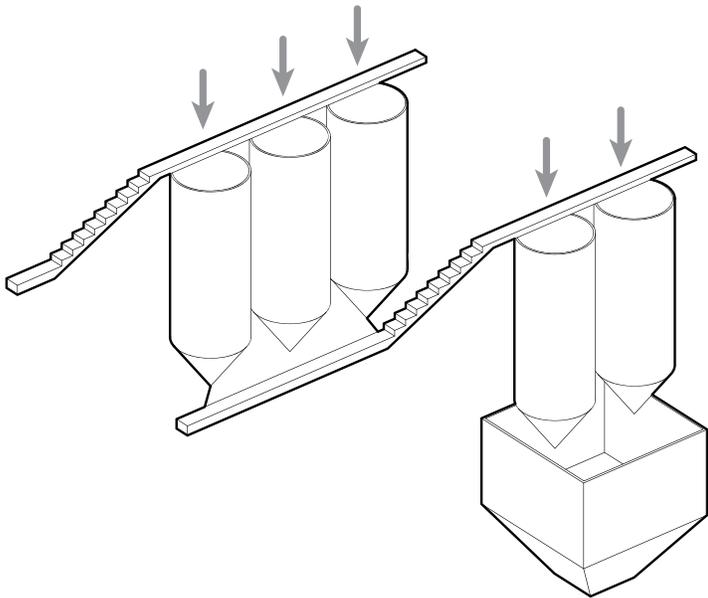
TRANSPORT



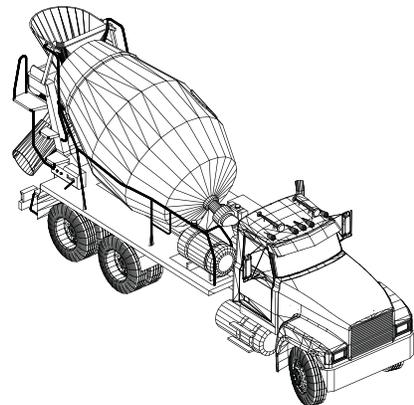
STOCKPILING



TRANSPORT



STORAGE SILOS - SAND, STONE, CEMENT MIXING
STORAGE - WATER & ADDITIVE MIXING



CONCRETE TRUCK TRANSPORT TO SITE



Fig. 2.10 Still from *Twenty-Four Blasts* film by Naoya Hatakeyama, 2011. Photo by Naoya Hatakeyama.

Fig. 2.11 (Facing) Limestone and sand mining process in Somerset, Kentucky. Photo by unknown.





Fig. 2.12 Concrete plant in North Chicago, 2009. Photo by Michael Dant.

Fig. 2.13 (Facing) Concrete pouring. Photo by Elliott Zone.



The materials are fed into large silos for further mixing and preheated to 1000° Celsius in the heat exchanger. The dust moves into the rotary kiln and is heated to 1450° Celsius, turning the mixture into clinker (small lumps), which is cooled briefly with air. The heating process uses either coal, natural gas, or oil, and sometimes recycled scrap wood for energy. Clinker is ground and mixed with additives such as gypsum or blast furnace slag and limestone dust, in order to create a setting regulator when the cement is mixed with water to cure. The cement mixture is funneled into a concrete truck and transported to the building site.⁸

The last of the three materials, steel, is something of an alchemical mystery, compared to timber and concrete. These two materials, we identify as primal in nature. Steel, however, is foreign in aesthetic and behaviour. Steel production uses small pieces of iron ore heated to temperatures that humans have only relatively recently developed for mass production. Steel can be molded into any shape fathomable. This process takes a great deal of energy and is therefore rated the weakest on the guidelines chart for *Ease of Manufacture*.

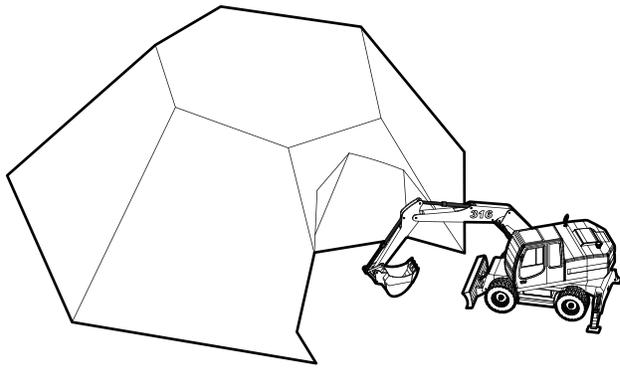
Raw material for steel—iron ore and coke (coal)—are extracted and mined in specific deposits throughout the world (figure 2.15). These materials are transported to a steel mill and added to a blast furnace through the top opening and heated to 1250° Celsius. Air is added through the bottom of the furnace. The melted ore and coal turn into molten metal and slag which is transported by a thick cast iron ladle and poured into an oxygen converter container heated to 1600° Celsius. This converter lowers the carbon content in the molten metal allowing it to become steel. A secondary furnace heats the molten steel to 1600° Celsius, drawing out impurities. Scrap metal can also be added to the secondary furnace after the scrap has been melted in a electric furnace. The molten steel is fed through a tundish, a mold for the steel, allowing it to cool. Before the milling process, the steel, called slab or bloom, is preheated to 1200° Celsius and fed through a billet and rolling mill to shape the steel into different products, such as I-beams, C-channels, and

Fig. 2.14 (Facing) Iron Ore mining in China, 2012. Photo by unknown.

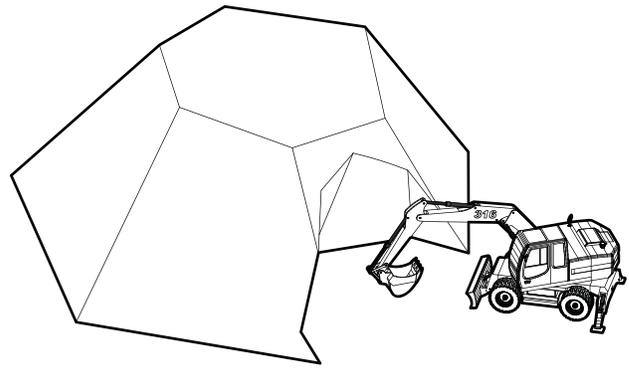
Fig. 2.15 (Following) Steel production process. Diagram by author.

8 Kula and Ternnaux, *Materiology*, 100.

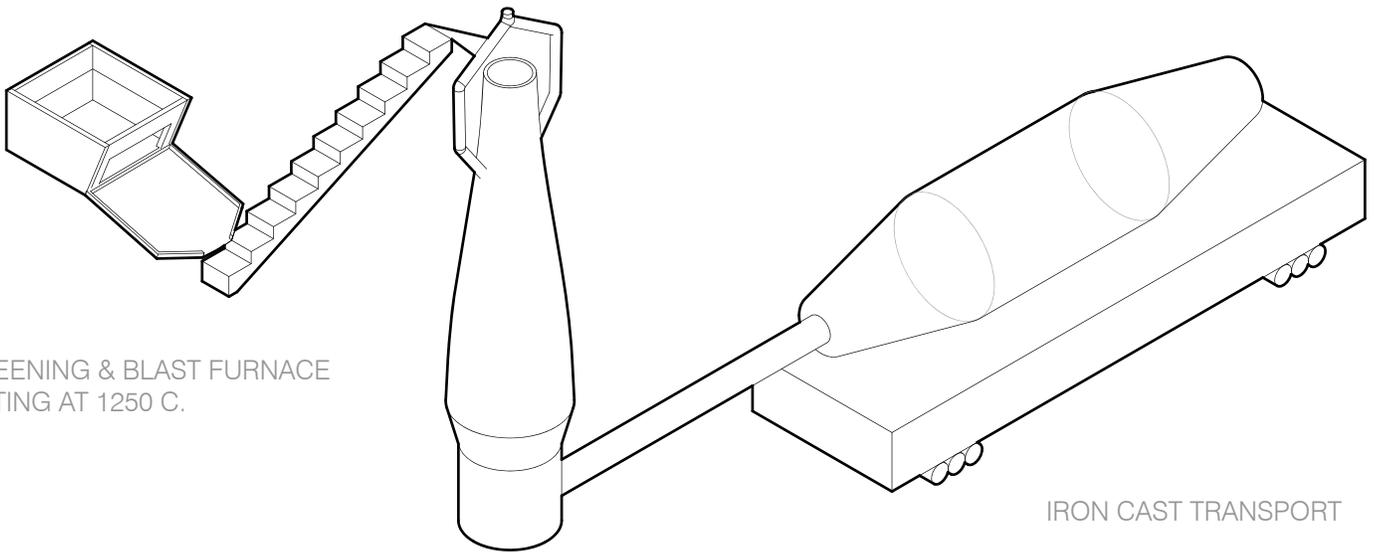




IRON ORE MINING & EXTRACTION

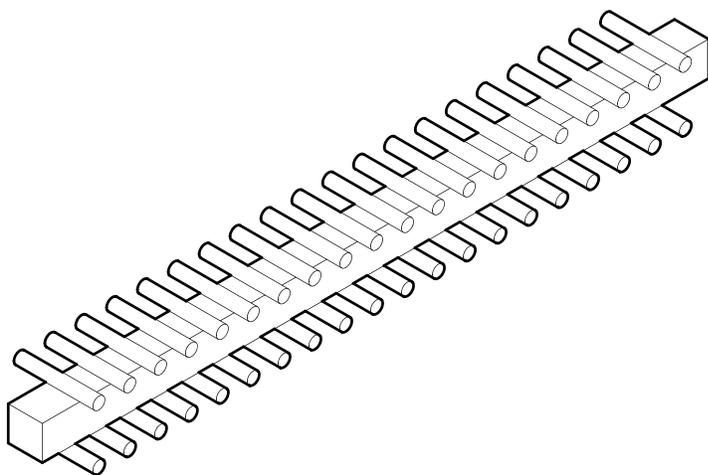


COKE (COAL) MINING & EXTRACTION

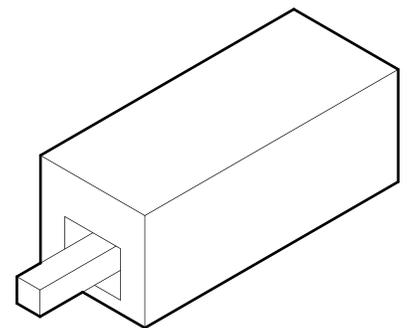


SCREENING & BLAST FURNACE
HEATING AT 1250 C.

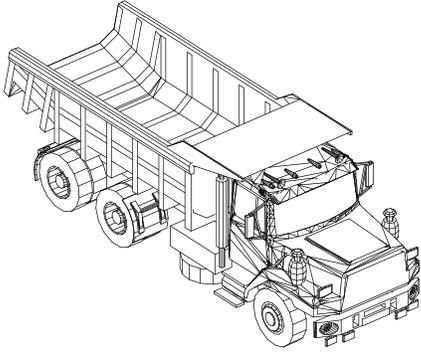
IRON CAST TRANSPORT



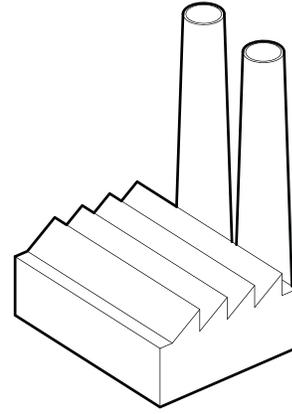
SLAB, BLOOM OR BILLET



PRE-MILLING FURNACE AT 1200 C.



TRANSPORT



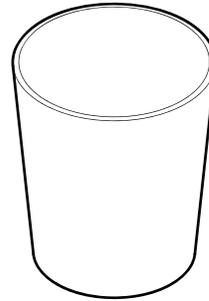
STEEL MILL PLANT



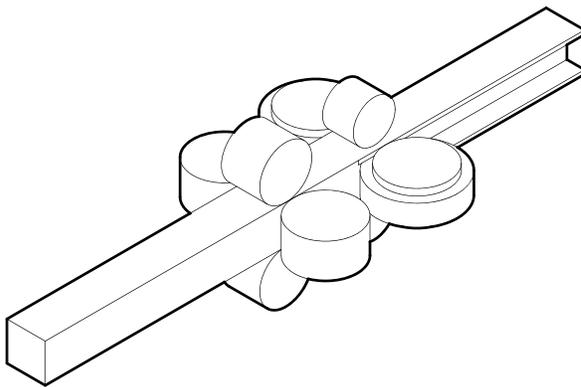
ELECTRIC FURNACE
AT 1600 C.



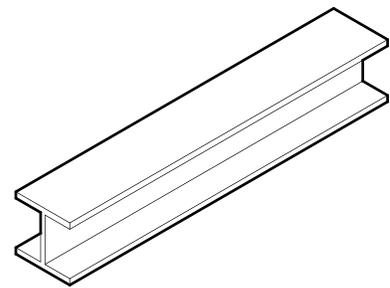
OXYGEN CONVERTER AT 1600 C.



SECONDARY FURNACE AT 1600 C.



ROLLING MILL

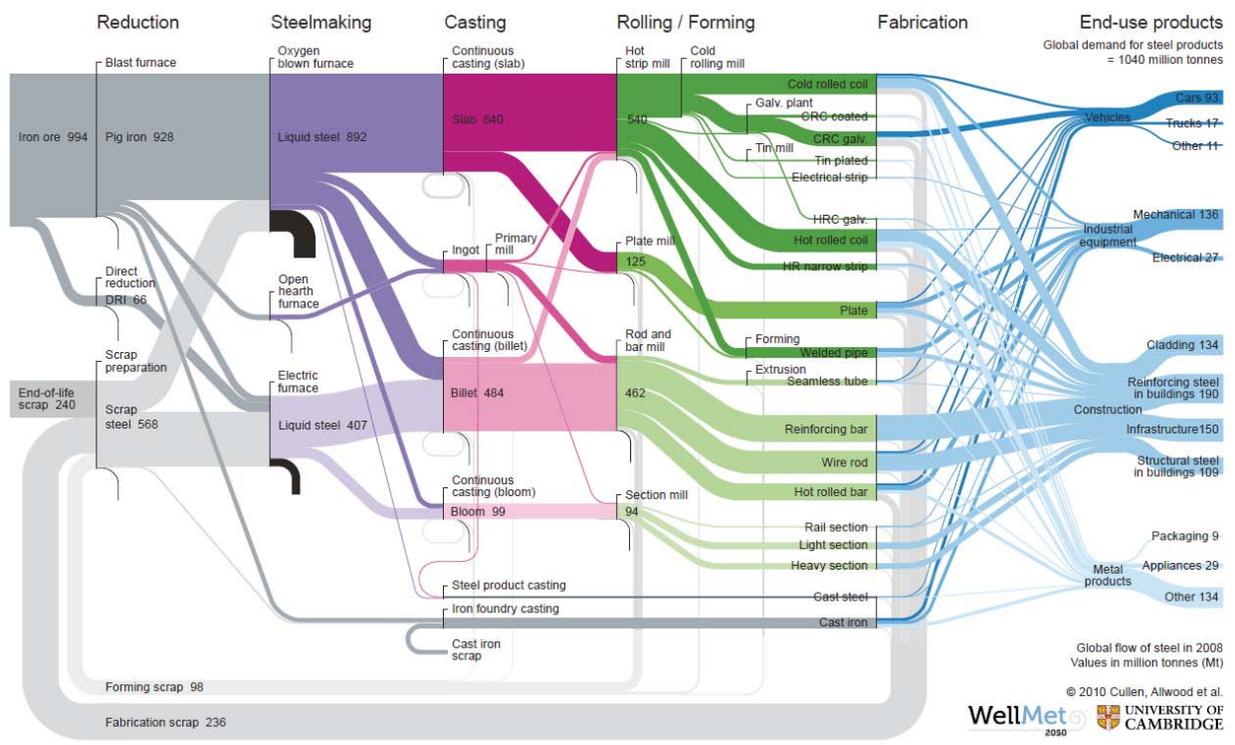


STEEL PRODUCTS



Fig. 2.16 Steel production process - oxygen converter ladle. Photo by unknown.
Fig. 2.17 (Facing) Steel production process - billet. Photo by unknown.
Fig. 2.18 (Following) Global flows of steel and aluminum, 2008. Diagram by Cullen and Allwood, University of Cambridge.





flat plates.⁹ The fabricator orders the necessary steel members cut to the appropriate sizes from the steel mill. The fabricator creates all the detailed connections for each member, based on the engineer and architects drawings. Bolt hole cuts are marked using a template and machine punched or drilled. Metal plates and angles are cut to size. Each steel member connection is finished as much as possible before being delivered on the construction site for assembly. Steel angles, plates, and tees are bolted or welded to the members in the fabrication shop. The finished members are labeled and stacked in order of assembly. The erectors load the members onto trucks and transport to the construction site.¹⁰

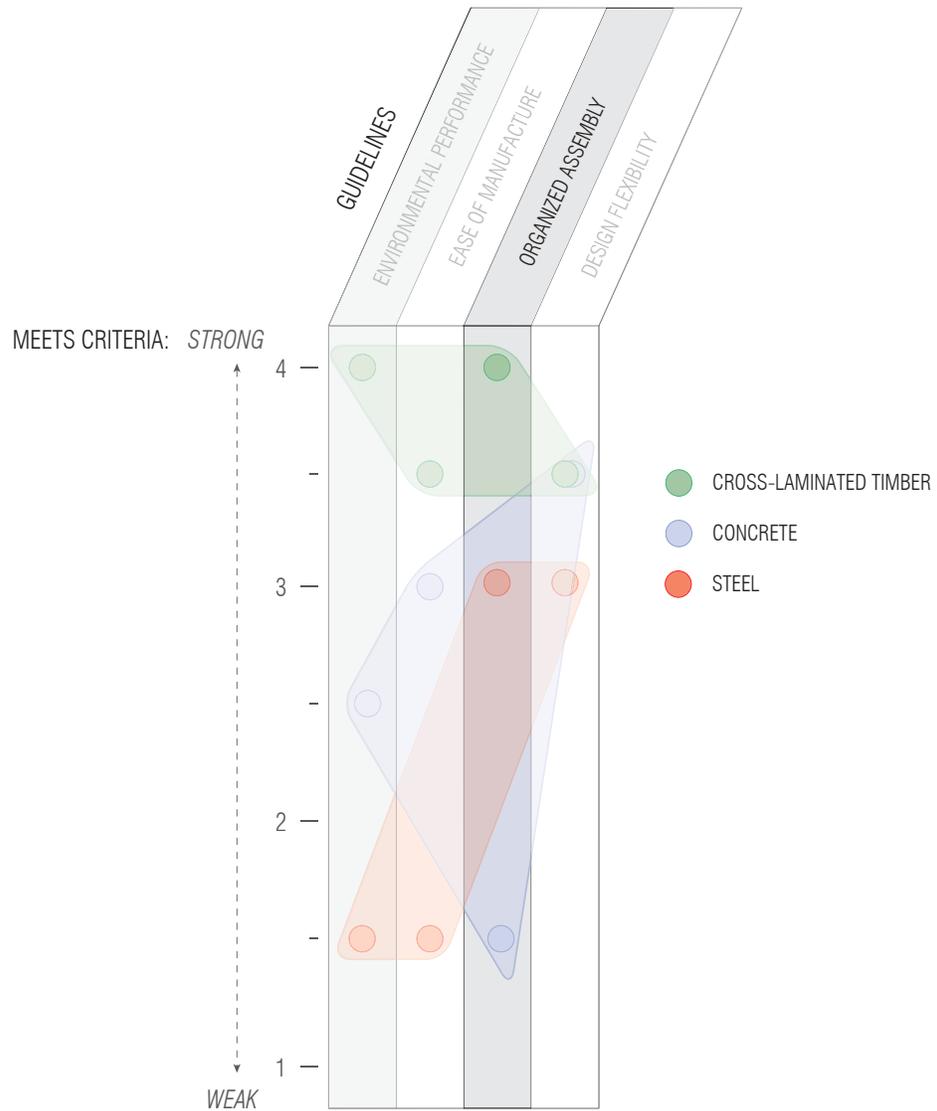
Ease of Manufacture for cross-laminated timber, concrete, and steel will only become more vital in the future as energy and resources become more costly. Recycling and new innovations in material mixtures and heating supply will play a large role. However, realizing the potential in working with responsibly harvested forests and cross-laminated timber production is bound to become a major force.

9 Ascher, *The Heights: Anatomy of a Skyscraper*, 52.

10 Allen and Iano, *Fundamentals of Building Construction*, 455.

The more distant loci of control, the increase in the quantity and specificity of abstract documents of control, and the growth of a litigious atmosphere in the construction industry and in the building culture as a whole have developed hand in hand. Together they have removed people's ability to carefully apply human discretion to the making of the building and have contributed to the abstract and fragmented nature of the modern built landscape."

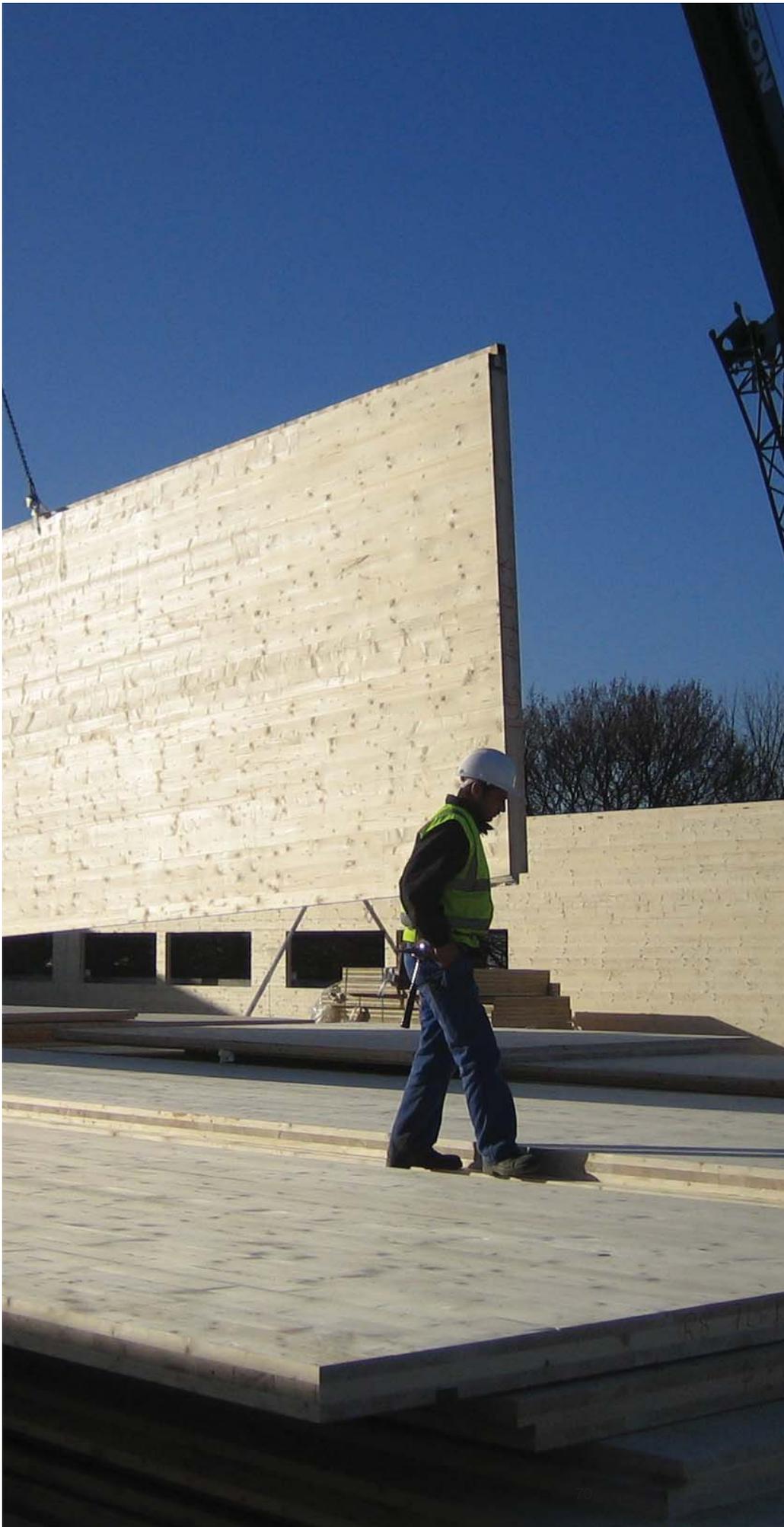
- Howard Davis, *The Culture of Building*, 2006. 200.



3.0 ORGANIZED ASSEMBLY

Rating: Cross-laminated timber 3.5/4. Concrete 1.5/4. Steel 3/4.

Cross-laminated timber panels are prefabricated in a factory using a CNC machine. The precision and controlled working environment, in collaboration with the architect and engineers, allow a streamlined and organized on-site assembly process. Concrete can be easily manipulated on the construction site, but needs an infrastructure of formwork, concrete trucks and pumps, and specific climatic conditions to cure properly. Steel members are prefabricated at a shop based on the architect's drawings. Assembly on-site is therefore straightforward, yet steel is much heavier to work with and requires welding and/or bolting.





Organized Assembly

Buildings have always been assembled with specific parts to form a whole, while some parts or components are prefabricated more so than others. The degree that building components are fabricated prior to being assembled on site affects costs, construction time, and overall quality. Architects must weigh several factors—cost savings, aesthetic desires, and functional needs—against one another in order to determine an appropriate construction system for a specific project.

Finding a balance between organized on-site assembly and design flexibility is important for the health of the architecture and building culture. As timber, concrete, and steel producers develop new innovations in material and building systems, on-site assembly—how workers and designers interact—is rapidly changing.

Building Information Modeling (BIM), a computer-aided-design and management tool, has increased the ability for architects, building consultants, and tradesmen to streamline the workflow from design to construction (figure 3.10)¹.

Coordinating the material on-site is integral to the execution of a project. Each building material presents challenges. Cross-laminated timber maintains the highest rating on the guidelines chart (figure 0.8) compared to concrete and steel. Cross-laminated timber panels are manufactured and fabricated by specific companies, such as KLH, Structurlam, etc., with skilled carpenters, technicians, and in-house engineers working as a team alongside the architect. The cross-laminated timber fabricators are included in the design process at an early stage. This ensures that wall, floor, and roof connection details are thought-out and organized for fabrication.²

Cross-laminated timber is essentially a heavy timber panel, similar to a concrete panel or slab, yet a fifth of the weight, and, in terms of connections and insert detailing, much easier to shape. With CNC machining at the fabrication plant, openings for windows and doors can be easily milled. Complete window and door assemblies in the panels are currently being innovated for prefabrication, ensuring more precise fittings for air tightness and water proofing. The connections for panel-to-

1 Eastman, “What is BIM?,” 16.

2 “The Product,” last modified 2014, <http://www.klhelement.com/en/produit>.

Fig. 3.1 (Previous left) CLT assembly. Photo by KLH UK.

Fig. 3.2 (Previous middle) One Bloor East foundation concrete pour, 2013. Photo by Jack Landau.

Fig. 3.3 (Previous right) Hearst tower steel assembly. Photo by Foster and Partners.

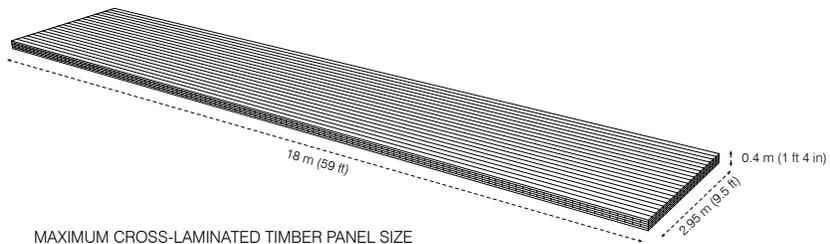
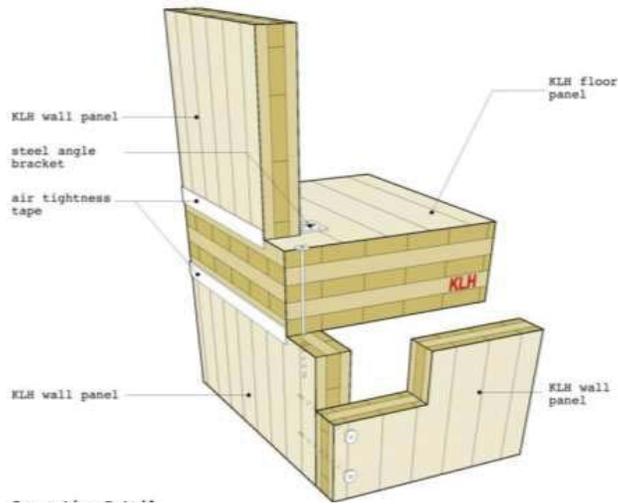
panel—whether it be floor-to-floor, wall-to-floor, or wall-to-ceiling—is straightforward (figures 3.4-3.8). Most of the time, long self-tapping screws are used and, in some cases, traditional wood joinery is used to increase the strength of the connection. Panels can be routed with a CNC machine for notching and half-lapped connections. Dowels or rods, similar to traditional heavy timber mortise and tenon joints, and dovetail joints with metal brackets are also used. Other connections, such as standard exposed metal brackets, which are easy to install but have less fire resistance, or concealed metal plates with bolts or screws, are more ideal for stronger assemblies. Many connection details depend on specific load conditions and if the panel will be left exposed on the interior of the building.³

Overall the cross-laminated timber assembly process is straightforward and efficient compared to concrete and steel systems. The panels are manufactured in a controlled facility, with carpenters working alongside architects and engineers. The panels are flat packed onto trucks with numbered directions indicating the assembly sequence and connection to each panel. Small holes—for slings, plates, or steel eyelets—are drilled into the panel for on-site crane lifting. Ideally, trucks with panels should arrive according to the construction schedule. However, if there is space on-site for panel storage, a temporary elevated bed is assembled and the panels are stacked on top and covered with a protective waterproof tarp.⁴

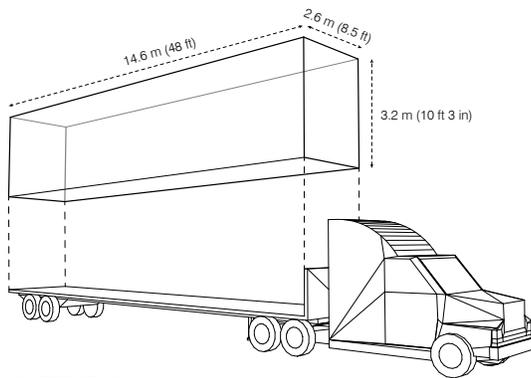
Concrete construction, while easily manipulated and used in the majority of construction projects, is not simple and straightforward. Compared to timber panels, concrete uses a huge amount of formwork, and needs specific, ideal climatic conditions to cure properly. There are two main forms for concrete construction: (1) in-situ concrete (otherwise known as cast-in-place concrete), where the concrete is poured and cured directly on the building site, and (2) precast concrete, a panel based concrete form fabricated off-site in a facility. Precast concrete is used in a prefabricated concrete frame and for tilt-up panels. Precast concrete is most similar to cross-laminated timber panels, however it is much heavier to assemble,

³ Gagnon and Pirvu, eds. *Cross-Laminated Timber Handbook*, ch. 05.

⁴ “Cross Laminated Timber (CLT),” last modified 2014, <http://woodworks.org/design-with-wood/building-systems-clt/>.



MAXIMUM CROSS-LAMINATED TIMBER PANEL SIZE



MAXIMUM TYPICAL FLATBED TRUCK

Fig. 3.4 (Top) Wall to wall and ceiling to wall connections. Diagram by KLH UK.

Fig. 3.5 (Bottom) Typical maximum dimensions for CLT panels and flatbed truck. Diagram by author.

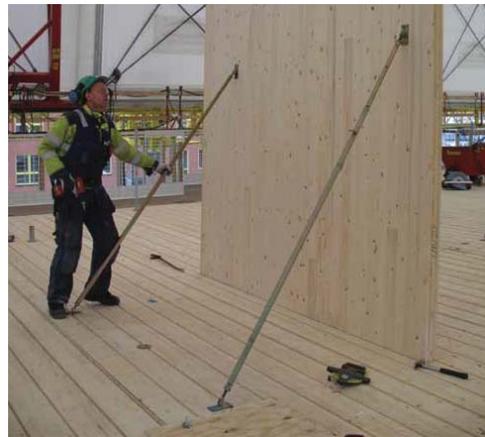


Fig. 3.6(Top) Half-lapped panel-to-panel connection. Photo by CrossLam Timber Solutions LLC.

Fig. 3.7 (Left) Panel-to-panel double internal spline connection. Photo by Kevin Meechan.

Fig. 3.8 (Right) Beam grip for tightening connections. Adjustable steel shores during assembly. Photo by FPInnovations.

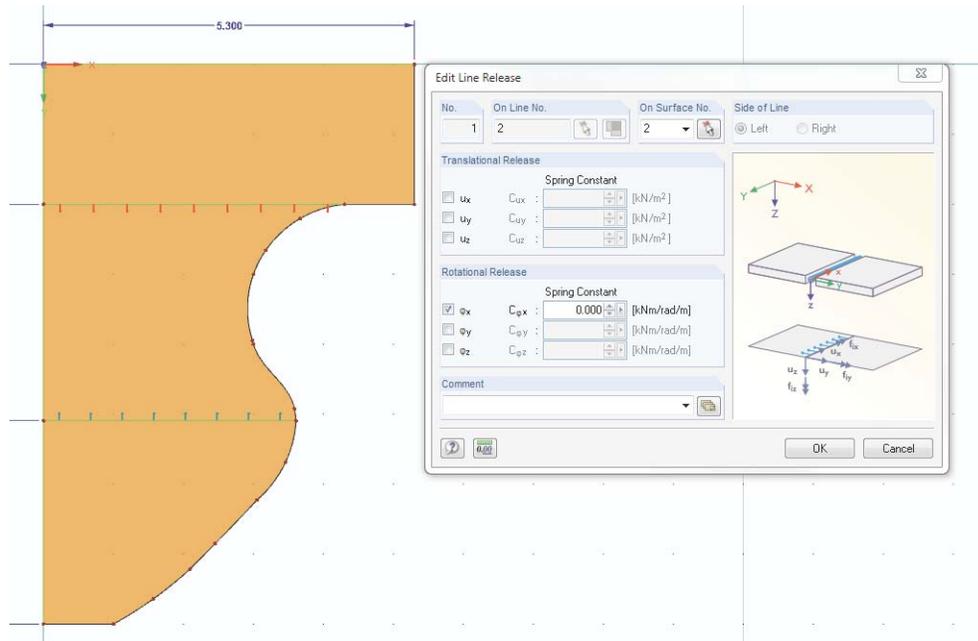
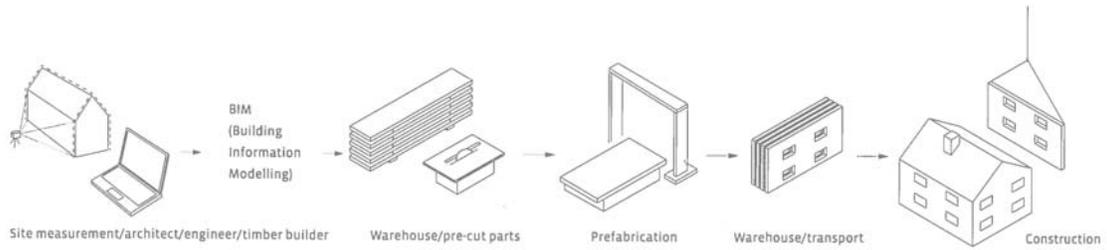


Fig. 3.9 (Top) BIM and construction process diagrams. Drawing by Kaufmann and Nerdinger, ed.

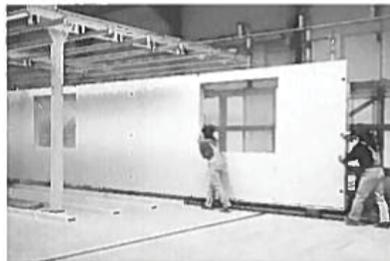
Fig. 3.10 (Bottom) BIM CLT modeling software. Photo by Bastian Kuhn.



Production plant for large-format wall elements: fabrication table



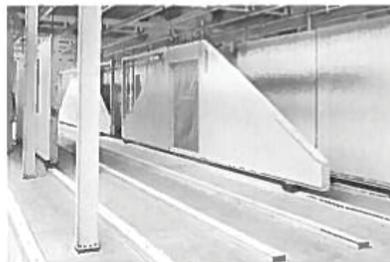
Transport of wall elements



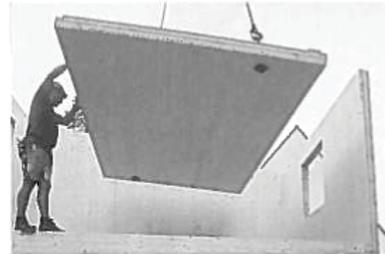
Assembly table



Erection of wall elements



Storage



Erection of floor elements

Fig. 3.11 Production and assembly of timber wall elements. Photos by Kaufmann and Nerdinger, ed.

constraining the design. Most precast concrete elements are standardized, such as fire stairs, mainly because of cost factors.

Concrete, as a material in construction and assembly, has inherent contradictions. While the most plastic material available for construction—in that the liquid material can be cast into any imaginable form—the building must be built twice almost. First, the building must be built in formwork, usually taking the shape of wood boards or panels. Second, it must be built in poured concrete. Modular formwork, used in repetitive conditions with standardized substructures, can streamline the formwork assembly process. Depending on the desired exposed concrete surface, wood boards are still used in conjunction with the modular system.⁵

Concrete also needs a substantial amount of reinforced steel rebar and mesh integrated into the formwork. Concrete works best in compression. The steel rebar allows concrete to resist tensile stresses, something concrete does not naturally do. Some concrete structures use so much steel rebar, one has to wonder why concrete would be used in the first place. The rebar has to be covered with at least three centimeters of concrete, protecting the steel from corrosion by air and water. Once the rebar and formwork, with construction joints, are in place, the wet concrete mixture is poured and set to cure. The concrete is compressed by vibration to clear the air pockets and to make sure the wet cement surrounds the rebar, filling the formwork. The curing process is incredibly important, because it ultimately dictates how the concrete will perform in the future. The concrete mixture must not dry too fast, which may cause cracks, but also must not be over-watered, causing efflorescence, a lime deposit in water appearing on the surface. Exposed concrete must be covered with a tarp, and if poured in the winter must be protected by a heating device or coverage so as not to freeze. Compared to cross-laminated timber and steel assembly systems, concrete is cost-effective but the process is error-prone and can result in long-term problems for a building.⁶

5 Staib and Dörrhöfer, *Components and Systems: Modular Construction - Design, Structure, New Technologies*, 65.

6 Deplazes, *Constructing Architecture: Materials Processes Structures - A Handbook*, 63-64.

Fig. 3.12 (Facing top) Condo NY2 development concrete construction in Toronto. Photo by Jack Landau.

Fig. 3.13 (Facing bottom) Wood formwork being taken off in-situ concrete wall. Photo by unknown.



Steel assembly is relatively straightforward because it is based on a skeletal framing system with steel columns and beams bolted and/or welded together. The steel assembly is similar to cross-laminated timber. It arrives on a flatbed truck based on the construction schedule, organized with markings for workers to bolt together in the correct sequence. Steel skeletal framing systems can benefit from long spans, either set in a grid internally or externally. Connections are designed based on several factors—whether the structure will be exposed or covered, the specific load, and economic factors such as assembly time and dismantling at the end of a building’s life cycle. Bolts are the most common method, allowing quick assembly and dismantling for future use, taking on shear stress loads and tension.⁷

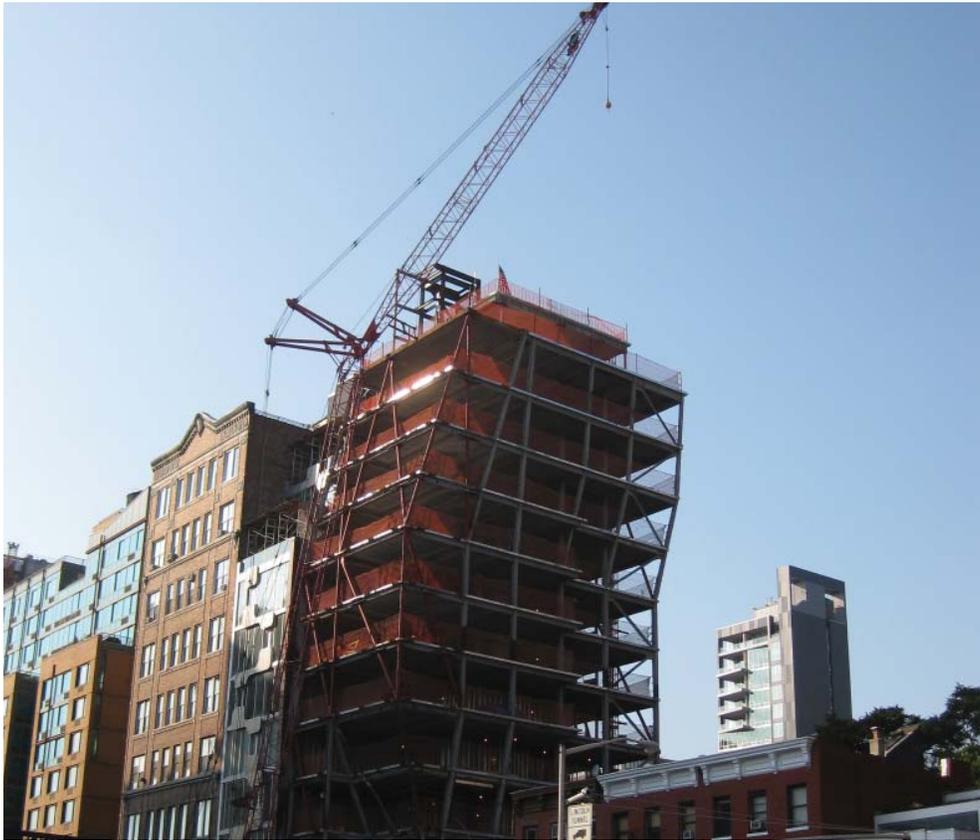
Unlike cross-laminated timber and concrete, where most of the building can essentially be composed of a single material, steel framing relies on other materials for wall and floor infill. The most common materials are steel decking with a concrete floor slab and lightweight partition walls. This composite method is more economic than steel alone, but it is still expensive due to steel’s inherent cost.

Providing an organized assembly method is crucial to ensure common errors are eliminated on site. Architects and tradespeople are realizing the benefits of shaping structural materials off-site in a factory in order to create a better assembly system and, in turn, a better performing building. Cross-laminated timber, especially in Ontario, fits the criteria, making it a great competitor, in custom fabricating panels off-site, and using a locally available and economical material.

⁷ Staib and Dörrhöfer, *Components and Systems: Modular Construction - Design, Structure, New Technologies*, 58.

Fig. 3.14 (Facing top) Ironworker connecting a steel plate to a column at One World Trade Center in NY, 2010. Photo by Mark Lennihan.

Fig. 3.15 (Facing bottom) Steel frame assembly erection at HL23 in NY by Neil M. Denari Architects, 2009. Photo by author.



Case Study - Kaden Klingbeil Architects - E3 Berlin

Esmarchstrasse 3, or *E3*, is a seven-storey multi-unit residential building in Berlin, Germany based on the *Baugruppen* development system. In the *Baugruppen* system, a group of people who come together to develop a project. It is a way for the collective to create affordable custom home ownership by eliminating the developer, saving approximately 20 percent of the overall cost.

E3 by Kaden Klingbeil Architects, is a prime example of the *Baugruppen* system. They decided to use engineered timber post and beams with six inch cross-laminated timber infill panels to build a sustainable, yet cost-effective building. The posts and beams, 24 inches by 26 inches, are CNCed to slot together using three different types of steel knife plate connectors. This expedites and organizes the construction schedule. In eight weeks, four carpenters on site erecting one floor per week enclosed the building. The site, an urban infill development, had limited space for storing materials. The architects saw a logical opportunity to use a prefabricated construction method.¹

At the time of design in 2005, Berlin had just updated their building code to allow for timber to be used in five-storey buildings. Tom Kaden and Tom Klingbeil had to negotiate with the Berlin building authorities in order to use timber in a residential mid-rise development, helping to set a standard for timber in cities. The stairs were set apart from the building and encased in concrete construction. *E3* finished construction in 2008, making it the first seven-storey timber apartment building in Berlin. Along with a timber structure, Kaden Klingbeil used geothermal heating and solar panels to reduce operating costs for the *Baugruppen* collective.²

1 "e_3: housing in berlin by Kaden Klingbeil Architekten," last modified October 2, 2009, http://architecturelab.net/2009/10/e_3-housing-in-berlin-by-kaden-klingbeil-architekten/#lightbox/1/

2 "Berlin, Germany E3, Berlin," last modified December 10, 2012, <http://architectureindevelopment.org/project.php?id=318#!prettyPhoto>

Fig. 3.16 (Facing top left) *E3* residential apartment under construction in Berlin. Photo by Kaden Klingbeil Architekten.
Fig. 3.17 (Facing bottom left) Detail of engineered timber post and beam with metal plate connections. Photo by *ibid*.

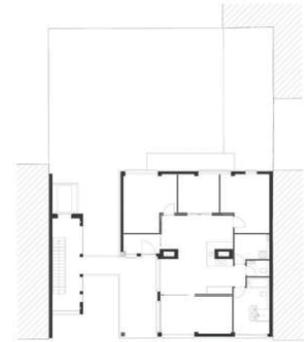






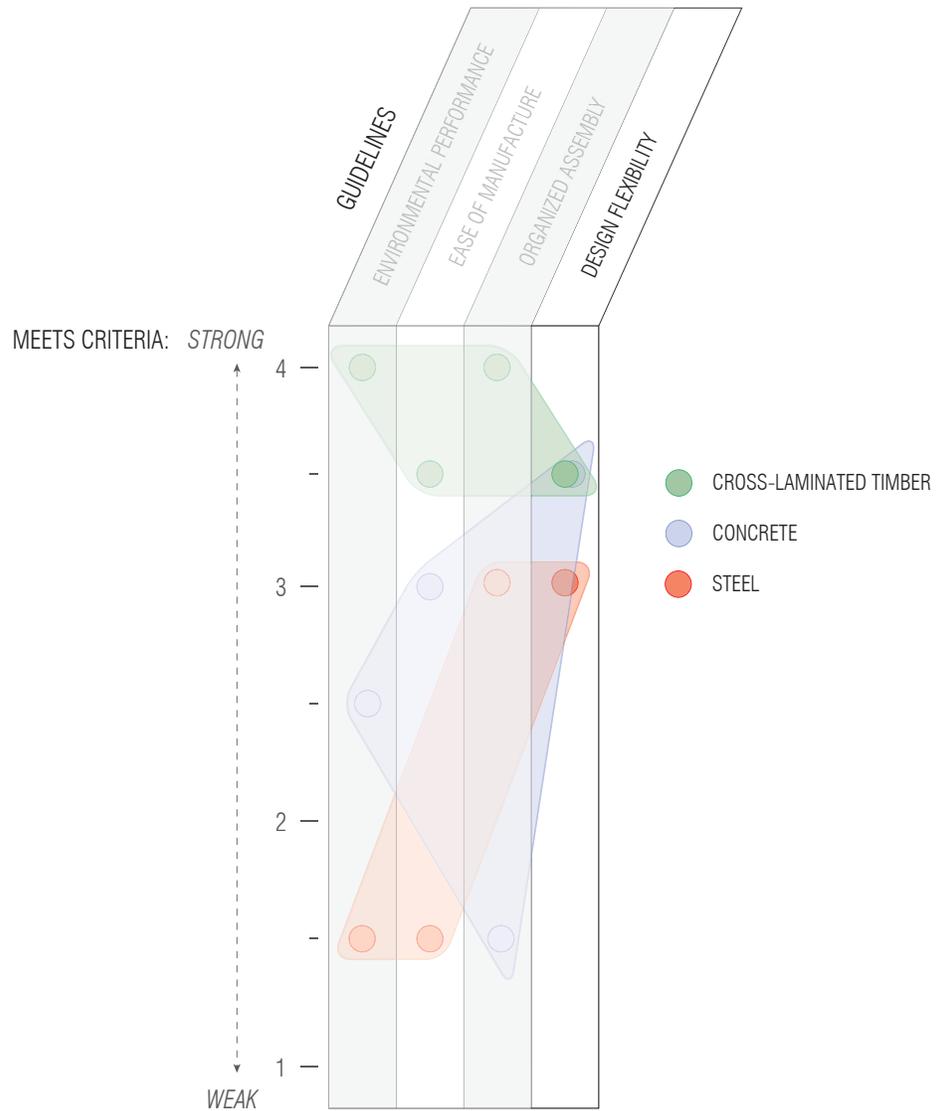
Fig. 3.18 (Facing top) View of the front facade. Photo by *ibid.*

Fig. 3.19 (Facing bottom) View of the back facade. Photo by *ibid.*

Fig. 3.20 View of the interior. Photo by *ibid.*

“In a healthy, contemporary building culture, money flows in two ways: first, internally, in ways that reinforce the capabilities, economy, and social life of the building culture itself; and externally, in ways that bring in the best innovations, and good products that cannot be capitalized within the building culture itself, from outside. A balance is needed that results neither in isolation and stagnation nor in the elimination of the local building culture altogether.”

- Howard Davis, *The Culture of Building*, 2006. 180.



4.0 DESIGN FLEXIBILITY

Rating: Cross-laminated timber 3.5/4. Concrete 3.5/4. Steel 3/4.

Cross-laminated timber is an adaptable construction material, used for floor, walls, and roofs providing long spans. The panels can be used in buildings with steel, concrete, and heavy timber, and can be left exposed on the interior. Concrete is easily manipulated and can take the shape of virtually any formwork cast. Steel is highly controllable, yet is costly and difficult to work with on-site.





Developments in Building Culture

Prior to the recent interest in ecology, nature was not thought of as the object of the activities of capitalism; rather it was thought of as the arena in which capitalism and social life and each individual life had its being. Aspects of nature were objects of scientific study, but nature-as-a-whole defied possession.

- John Berger, *Ways of Seeing*, 1972. 105.

Economic value of a building material is subject to variable conditions, such as manufacturing process and technology, resource availability, and popularity at the time. One must decide if timber, concrete, or steel is the best material for a specific project at a specific time and budget. Architecture, and the building culture we inhabit, operate in an ever-evolving dynamic system. The resources we use for buildings and everyday products, such as packaging and light bulbs, are shaped by an economy. Timber, concrete, and steel have all fluctuated in demand depending on the economic environment of the time. Historically, building culture has responded to economic circumstances with new material innovations. The trends of timber, concrete, and steel have responded in relation to the geopolitical and technological developments at the time.

Concrete, steel, and timber have all gone through cycles of change. Wood was the primary resource used before the 20th century because of its accessibility and cost. The Industrial Revolution cast timber aside as a primary building material. In countries throughout Europe, forests were exploited for fuel to increase production of steel and concrete. In England, forests decreased to 5% of total land coverage in the early 20th century, having been about 15% (figure 4.2). Forest conservation was not thought of as a crucial issue, having had such abundant timber resources throughout history.¹

Widespread fires in cities became problematic, contributing to timbers decline in the building industry. Starting with the Great Fire of London in 1666, and escalating throughout the

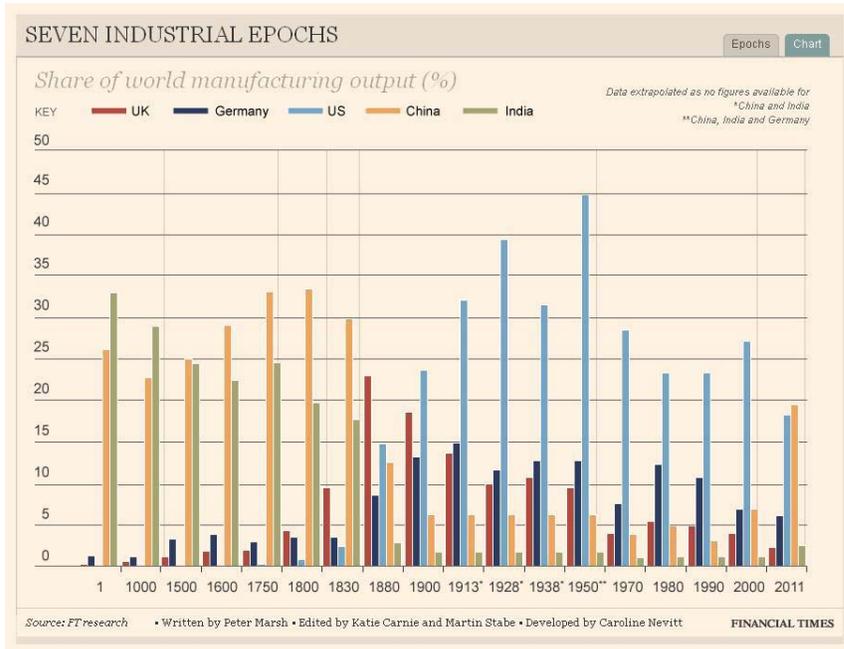
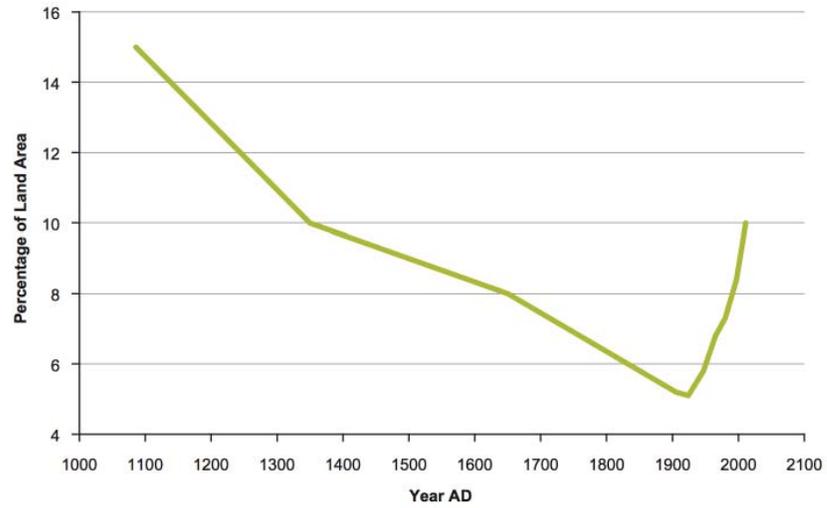
1 Kula and Ternnaux, *Materiology*, 14

Fig. 4.1 (Previous) Aerial view of Hull-Oakes Lumber Co. with expansion plans for new saw technology in Benton, Oregon, 1957. Photo by Gary Tarleton.

Fig. 4.2 (Facing top) Graph showing forest land coverage in England over 1000 year period. Diagram by Forestry Commission, England.

Fig. 4.3 (Facing bottom) World manufacturing outputs showing 5 countries. Diagram by Financial Times research.

Woodland as a percentage of land area in England





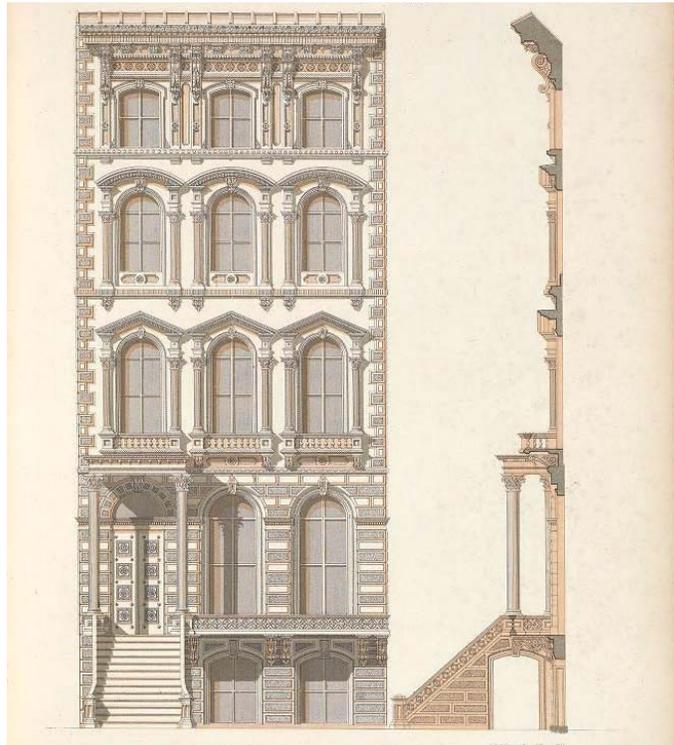
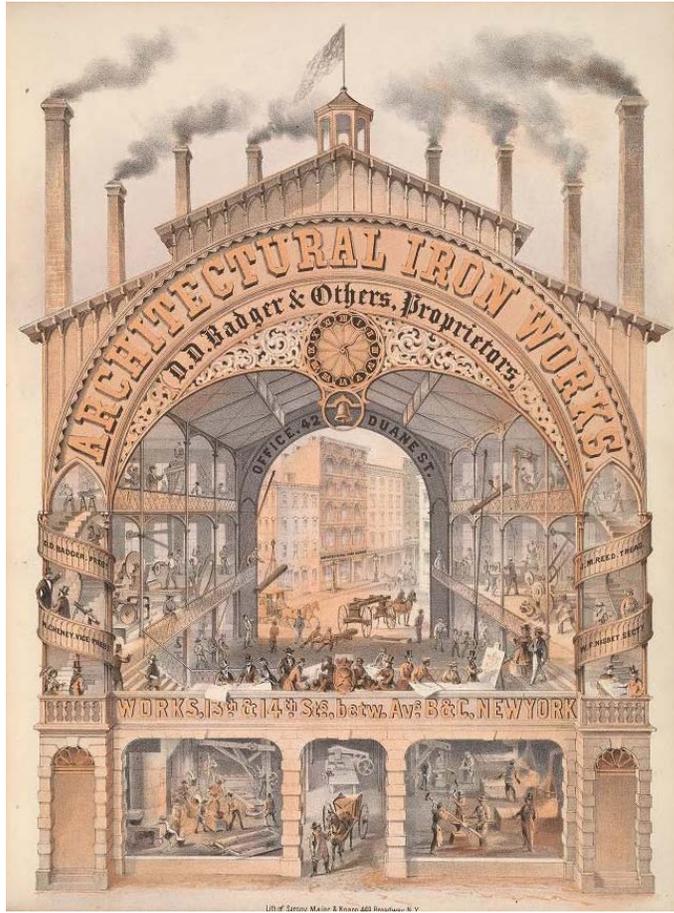


Fig. 4.4 (Facing top) Aftermath of fire in Toronto at Bay St. and Wellington St., 1904. Photo by Henry Fowlds Sharpe.

Fig. 4.5 (Facing bottom) View from street level, 1904. Photo by unknown.

Fig. 4.6 (Top) The office building of the Architectural Iron Works, 42 Duane Street, NY. Drawing by D.D. Badger and Co.

Fig. 4.7 (Bottom) Elevation and section of Iron Front for Dwelling-house. Drawing by D.D. Badger and Co.

Industrial Revolution with the Great Chicago Fire of 1871, and the Great Fires of Toronto in 1849 and 1904, building codes began to change, limiting use of wood in buildings. Cast iron, steel, and concrete became cheaper to produce in the mid-nineteenth century, contributing to the decline of timber as a dominant structural material used in cities.²

Cast iron architecture was triggered by developments in the manufacturing process in the mid-eighteenth century. Engineers discovered how to increase the heat in furnaces to the point where iron could easily pour into casts. This advancement, first established in England, and utilized for bridges, created a wave of prefabricated elements in architecture. James Bogardus brought cast iron to New York and began making architectural components, such as columns, beams, lintels and panels that could be easily bolted together on site. Daniel D. Badger, inspired by Bogardus, built a foundry and factory for cast iron production (figure 4.8, 4.9). Cast iron allowed architects and builders to build ornate tall buildings modeled after Greek and Italian classical architecture. Cast iron could imitate the feel of stone, while allowing for quick assembly of the relatively light weight casts. The rise of cast iron led to advancements in structural steel, allowing for skyscrapers in Chicago and New York. Steel is simply iron with a lesser carbon content (iron has 2-6% carbon, steel has below 2%).³

Reinforced concrete was invented in 1849 and because of its fire safety, structural capabilities, and accessible manufacturing, it is now the most widely used material. Concrete is the most artificially produced material on earth, at one ton per year per person (figure 4.10, 4.11). However, wood is making its way back into construction in cities because of advancements in fire safety, ease of construction, and less energy needed in the manufacturing process.⁴

2 Buri and Weinand, "The Tectonics of Timber Architecture in the Digital Age," in *Building with Timber: Paths Into The Future*, 56.

3 Badger, *Badger's Illustrated Catalogue of Cast-Iron Architecture*, 1-10.

4 "The World's Most Advanced Building Material Is... Wood," last modified February 26, 2014, <http://www.popsci.com/article/technology/worlds-most-advanced-building-material-wood-0?dom=PSC&loc=recent&lnk=5&con=the-worlds-most-advanced-building-material-is-wood>.

The Environmental movement, starting with the 1973 OPEC oil crisis, was a catalyst in bringing awareness and attention to our limited natural resources. Additionally, more recent data on global carbon emissions has put pressure on, not just the building industry, but how we value our resources. Building Information Modeling (BIM) and accessibility to CNC machining has allowed engineered timber to make its way onto the market, with more custom cross-laminated timber panels, competing with the typical materials in architecture today.

CO₂ emissions from fossil fuel use and cement production per capita

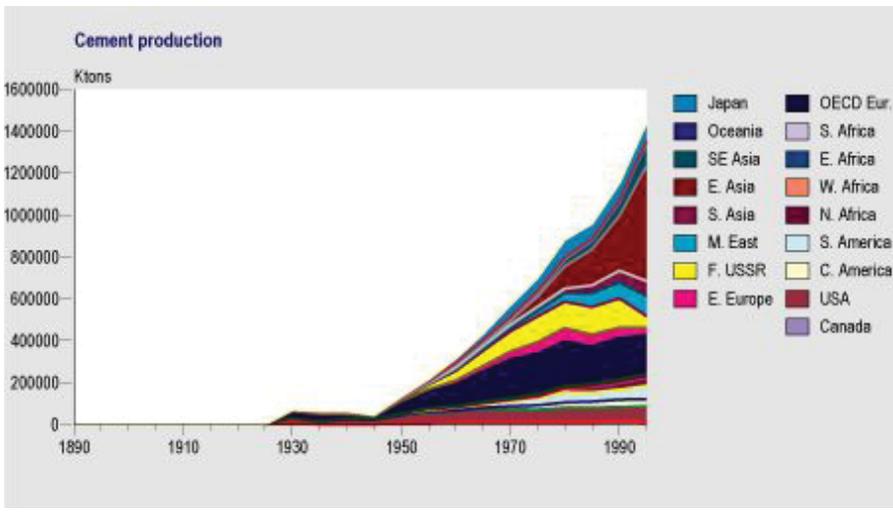
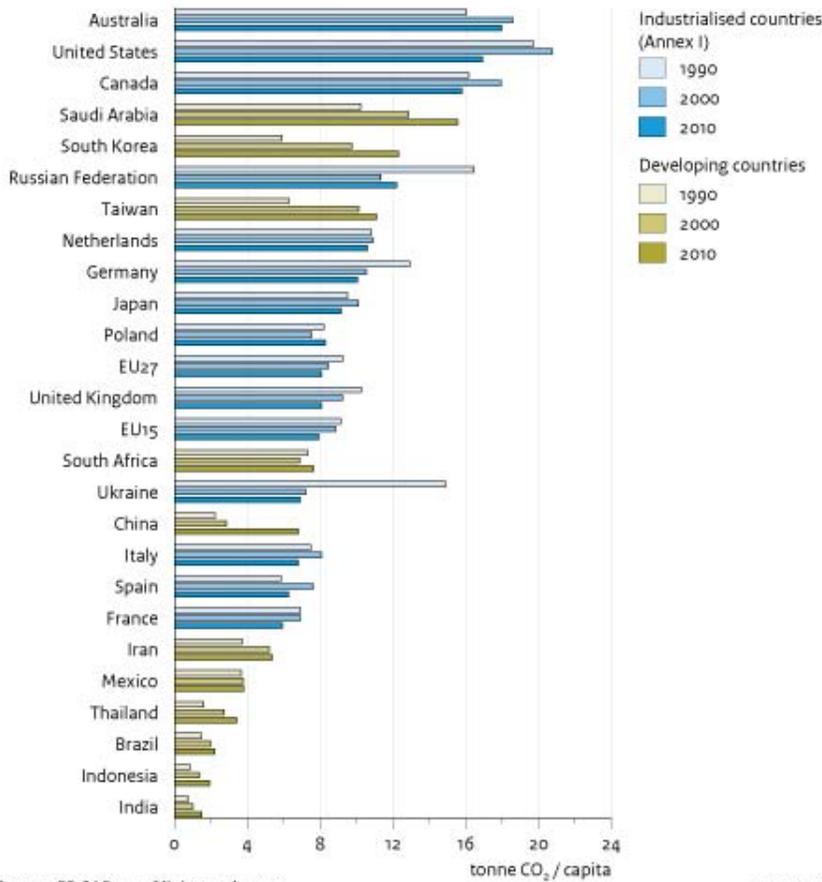
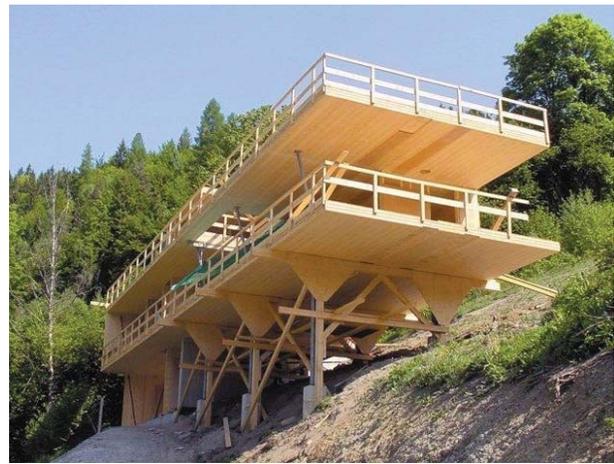
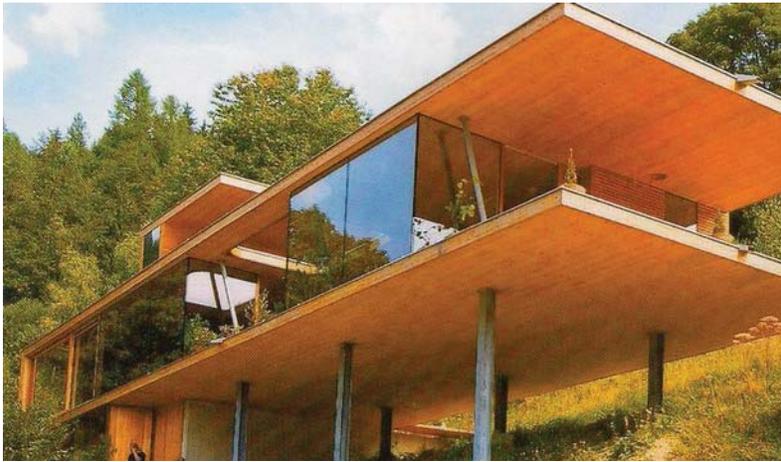


Fig. 4.8 (Top) CO₂ emissions from fossil fuel use and cement production per capita. Diagram by EDGAR 4.2.
Fig. 4.9 (Bottom) Cement production by country over a 100 year period. Diagram by Marland et al.

“What all of these works demonstrate in different ways is a mastery over the means of production and an ability to break down the construction of a building into its constituent parts and to use this articulation as a stratagem bestowing an appropriate character on the work in hand. This regionally inflected but universal approach highlights the crossroads at which the profession stands, for the fact is that either architects will maintain their control over the metier of building design, irrespective of the scale at which it occurs, or the profession as we know it will cease to exist.”

- Kenneth Frampton, *Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture*, 2001. 386.





Design Parameters

The architect must maintain a working dialogue between engineers, material manufacturers, and contractors, shaping the conceptual vision and capturing the poetics of construction in the final execution of the building. This interdependency, while presently looking bleak with a stagnant building culture in North America, has the potential to regain its footing. Cross-laminated timber is one material that enables design flexibility between the parties.

The adaptability of a project is limited by parameters, such as purpose, regulations, and costs. The previous chapters—*Environmental Performance*, *Ease of Manufacture*, and *Organized Assembly*—are key drivers in the building process. Timber's ability to adapt to these parameters, makes it as competitive as steel and concrete in design flexibility.

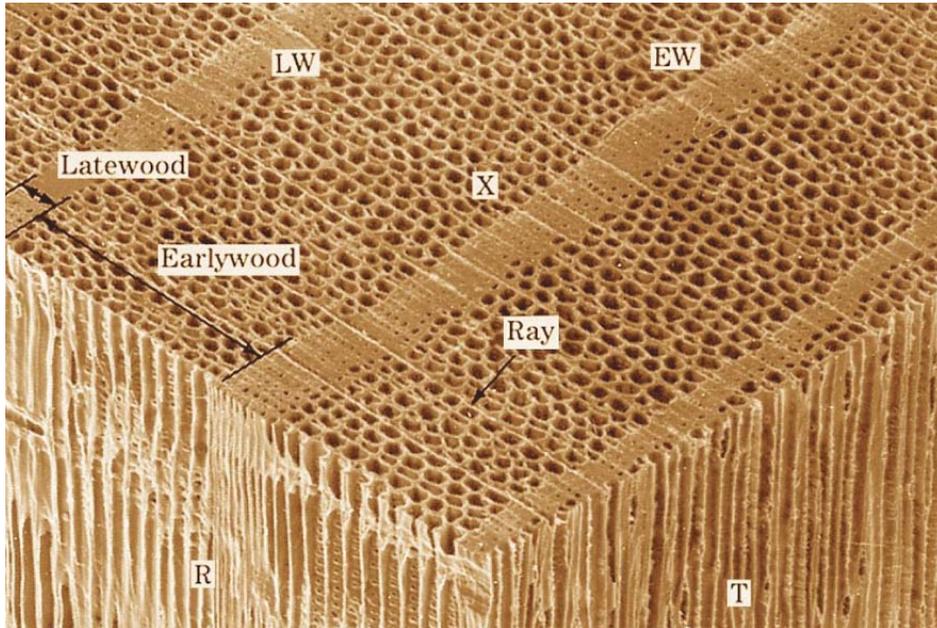
Depending on the project, the following structural factors must be considered. (1) Panel thickness: the architect must work with the engineer and manufacturer to specify the correct layering for the specified load. The panel layers are always odd numbered, ranging from three layers (99-109mm) to nine layers (240-250mm) and on special occasions up to eleven layers. (2) Span direction: the panels can work in multiple span directions for floor slabs but the longest span must follow the grain of the outer layer for greatest efficiency. For walls, the outer grain runs vertically, corresponding to the load direction.¹

Cross-laminated timber spans a greater distance with a smaller slab thickness than concrete and is approximately one fifth the weight. For example, in a typical residential building, a three layer, single span floor, 100mm thick can span up to 3.5 meters. A 150mm concrete floor slab in comparison, can only span 2.4 meters. Design flexibility is not only structural but allows for varied forms and composite materials. Cross-laminated timber panels can be integrated with engineered glulam columns and beams to adapt to longer spans and non-planar geometry. Metal connection plates create more structural flexibility if needed.² The panels can be left exposed on the

1 Gagnon and Pirvu, eds. *Cross-Laminated Timber Handbook*, ch. 03.

2 "The World's Most Advanced Building Material Is... Wood," last modified February 26, 2014, <http://www.popsci.com/>

Fig. 4.10 (Previous - selection of CLT building types starting from clockwise bottom-left) School complex in Rillieux-la-Pape, France by Tectoniques Architects. Photo by Renaud Araud.
Fig. 4.11 (Previous) Ibid.
Fig. 4.12 (Previous) House in Madrid, Spain by Elii and KLH. Photo by KLH.
Fig. 4.13 (Previous) Residential building in Altura, Spain by Ramon Llobera i Serentill Arquitecte. Photo by KLH.
Fig. 4.14 (Previous) Residential house in Koniz, Switz., by Halle 58 Architects. Photo by Halle 58 Architects.
Fig. 4.15 (Previous) Library and culture centre in Vennessla, Norway by Helen & Hard. Photo by Emile Ashley.
Fig. 4.16 (Previous) Ibid.
Fig. 4.17 (Previous) The Hive library in Worcester, England by Feilden Clegg Bradley Studios. Photo by Hufton & Crow.
Fig. 4.18 (Previous) Ibid.
Fig. 4.19 (Previous) Ibid.
Fig. 4.20 (Previous) House in Wohnbuhne am Hang by DI Ulli Koller and Thomas Stiegler. Photo by KLH.
Fig. 4.21 (Previous) Ibid.
Fig. 4.22 (Facing top) Sectional cellular view of soft wood. The lightweight and flexible properties make wood ideal for earthquake regions. Photo by Paulo Monteiro.
Fig. 4.23 (Facing bottom) Interior skylight of The Hive library by Feilden Clegg Bradley Studios. Photo by Hufton & Crow.



interior, showing not only the wood structure, but enriching material texture and qualities. Compared to standard drywall spaces, typical of most condominium developments, interior wood cladding contributes to material diversity.

Cross-laminated timber manufacturers are able to provide structural engineering and mechanical design insight from an early stage. As a result, architects are able to experiment and develop different approaches to massing. By taking part in this dialogue throughout the early stages, fabrication and construction become part of the process, instead of an afterthought. Compared to the standard construction bidding phase, where builders are not as familiar with the design, cross-laminated timber workers fabricate the panels off-site and can make immediate changes if needed.

One of the potential drawbacks to building with cross-laminated timber, however, is the need to have direct access to special machinery for fabricating the panels and erecting them into place. Compared to building materials like standard lumber and ready-mix concrete, where an individual or team with less experience in construction can undertake a do-it-yourself project, cross-laminated timber panels do require an initial investment. This can be a barrier to more artisanal construction projects. However, because there are many local softwood lumber companies who are capable of manufacturing cross-laminated timber, clients and home builders will have access to a high performance and custom design alternative.

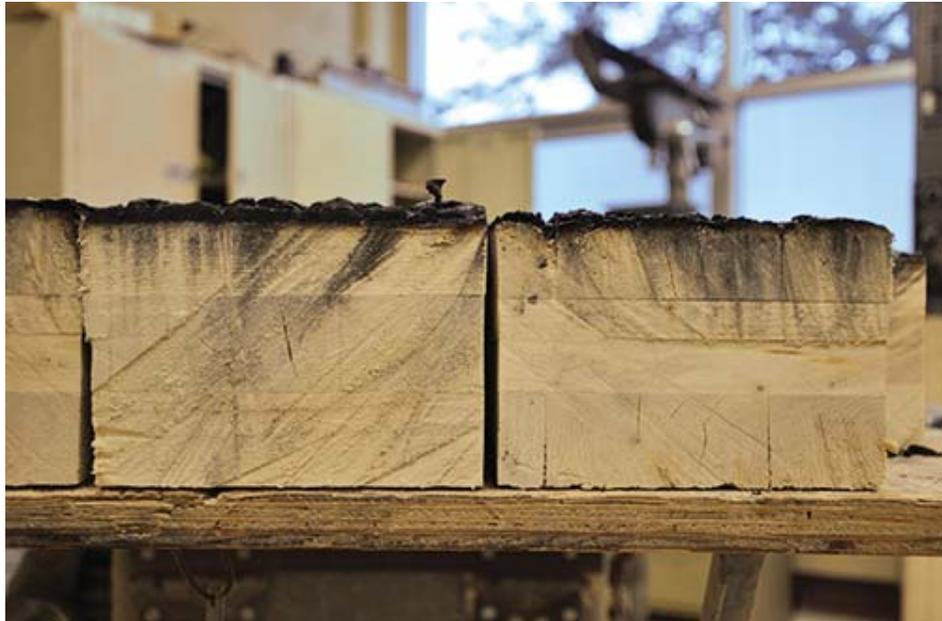
Maintenance for a building is inevitable regardless of the material. Most major structural restorations occur because of leaks over time, causing water damage to the structural members. This is a design and assembly problem from the start. As long as water is not trapped, and the panels are able to breath, moisture does not interfere with the building. However, if later renovations and restorations occur, cross-laminated timber is easy to work with, essentially being soft lumber, removed or replaced with ease.³

Fire safety, an integral factor for allowing heavy timber

article/technology/worlds-most-advanced-building-material-wood-0?dom=PSC&loc=recent&lnk=5&con=the-worlds-most-advanced-building-material-is-wood.

3 “Cross Laminated Timber (CLT),” last modified 2014, <http://woodworks.org/design-with-wood/building-systems-clt/>.

Fig. 4.24 (Facing) Fire testing on three-ply cross laminated timber panel. Photo by FPInnovations.



in buildings, has been rigorously tested, and competes with noncombustible concrete and steel in fire rating. Because of cross-laminated timber's solid nature, the outer layer slowly chars and inner part retains its strength for a longer period of time. The slow burning at a predictable rate, provides heavy timber with adequate fire resistance (figure 4.12). Most cross-laminated timber manufacturers can provide structural panels with a one hour fire rating and greater as required. While Ontario recently allowed timber in buildings up to six storeys, cross-laminated timber is still considered a combustible material, and is restricted for taller buildings. Sprinkler systems for timber buildings in Canada are used for precaution as well.⁴

Cross-laminated timber performs best in multi-residential housing projects. This is because the architect and manufacturer coordinate panel fabrication, taking advantage of the initial cost of transportation and crane assembly on the construction site. Because timber panels weigh much less than concrete or steel, standard building foundations do not have to be as intensive. Less concrete is needed in the foundations to support the lighter material, lowering the overall cost. The assembly system is also much quicker, reducing the overall construction budget by approximately 15 to 20 percent for mid-rise residential and non-residential buildings.⁵

It is difficult to pinpoint an accurate cost per square foot for Cross-laminated timber panels. This is mainly because the timber panel manufacturing ranges in thickness, CNC detailing, size of job, and potential waste from a specific job. The average manufacturing for the timber panels costs \$19 per cubic foot, and assembly is approximately \$15 per square foot. These costs compete with cast-in-place concrete, which has an average assembly cost for beams and slabs of \$17 per square foot, and walls at \$22 per square foot. In comparison, steel joists, beams, and columns are about \$15 per square foot for assembly. However, steel is expensive due to fluctuations in

4 Gagnon and Pirvu, eds. *Cross-Laminated Timber Handbook*, ch. 08.

5 Crespell and Gaston, "The Value Proposition for Cross-Laminated Timber," 1-19, <http://www.fpac.ca/publications/Value-CLT-2011%20NABC%20anaylisfinal.pdf>

manufacturing and transportation and the cost of wall and floor slab assemblies. These average cost comparisons provide an idea for the current construction values.⁶

Working relationships between specialized parties in the design and building process is key in realizing a project. However, design flexibility is not always as literal as it may sound. Beauty, while subjective, plays a leading role in shaping our surroundings. Cross-laminated timber, a simple innovation of an ancient material, might remind us where it comes from.

⁶ “Cross Laminated Timber (CLT),” last modified 2014, <http://woodworks.org/design-with-wood/building-systems-clt/>.

Case Study - ACME Architects - Hunsett Mill House, Norfolk, UK

The 213 square meter Hunsett Mill House is situated in the Norfolk Broads, a historic man-made wetland area in Norfolk, England. The artificial landscape consisting of canals, dykes, and water pumps was used for industrial production and is now being reclaimed as a conservation area. The design called for an extension to an existing small brick farm house once occupied by the keeper of the water pumping mill. By approaching the development with a light footprint, with energy conservation in mind, ACME designed a contemporary take on the pitched roofed dwelling with open light filled interior spaces.

The design was important in maintaining a low embodied energy goal and making sure the landscape was not disrupted throughout construction. ACME used cross-laminated timber as the main structural and interior finish material, with the solid timber panels creating the walls, floor slabs, and roofs of the house.

Design flexibility was an integral factor in using cross-laminated timber panels. The geometry for the folded pitched roof had to match the interior partition panels, allowing the floor plate to be more flexible providing larger open spaces. The panels minimized the amount of other materials needed because of their inherent thermal mass and insulating R-value. The interior was left exposed as well to show the wood finish and structural expression.

The exterior was clad in charred cedar boards, a traditional Japanese technique used to naturally treat and preserve timber. The dark wood charring was also used in surrounding Norfolk buildings for boat quays.

The use of cross-laminated timber panels enabled minimal concrete foundation construction because of its comparative lightness. The foundation piles were engineered to smaller diameter cylinders compared to standard concrete or steel construction. The timber panels were fabricated off-site using a detailed model of the house structure and panel layout along with pre-fitted services. The planning stage allowed for optimal CNC milling and reduced waste. Construction on-site was therefore minimal and was assembled in 2 weeks time.¹

¹ "Hunsett Mill House, Norfolk, UK," last modified December 13, 2010, <http://arqa.com/english/architecture-es/hunsett-mill-house-norfolk-uk.html>.

Fig. 4.25 (Facing top) CLT panel digital model for Hunsett Mill house in Norfolk, England by ACME. Photo by Cristobal Palma.

Fig. 4.26 (Facing bottom) CLT assembly and construction. Photo by ibid.

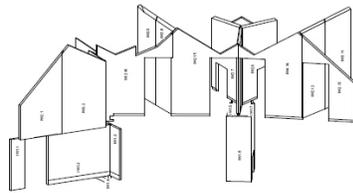
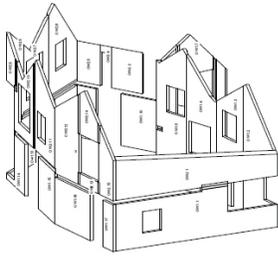
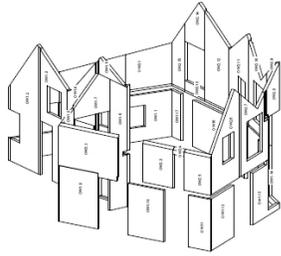




Fig. 4.27 (Top)
Fig. 4.28 (Bottom)



Fig. 4.29 (Top)
Fig. 4.30 (Bottom)

Case Study - Skidmore, Owings & Merrill - The Timber Tower Research Project, Chicago

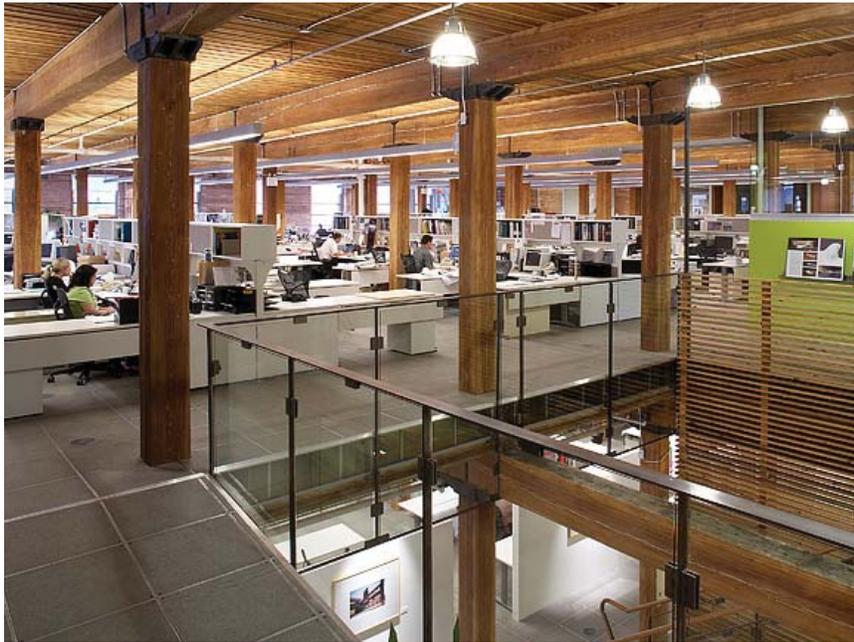
Adaptive reuse of buildings is common in contemporary cities, where an existing buildings design and structure, as well as physical condition, outweigh the need for demolition. Timber post and beam construction was used during the nineteenth and early twentieth century for factory buildings, (figure _), allowing an open floor plan for maximum flexibility. The skeletal framing system, largely transferred from heavy timber to steel and concrete, is being proposed in taller buildings using cross-laminated timber as the primary material.

Cross-laminated timber buildings, primarily ideal for mid-rise residential, commercial and mixed-use buildings, are based on a shear wall structural system. The timber panel, varying in thickness, in most cases from a greater thickness at the lower floors to a smaller thickness at the top floors, carries the load directly through its walls. This structural layout, unlike the standard post and beam skeletal grid, must be acknowledged and designed for accordingly. The shear wall system can be considered a drawback for a pure cross-laminated timber building particularly in taller structures. However, taller timber buildings are currently being proposed as a realistic solution, with cross-laminated timber used in conjunction with heavy engineered timber posts and beams and a minimal amount of concrete or steel.

The Timber Tower Research Project, is a recent proposal by Skidmore, Owings & Merrill (figure 5.25, 5.26). The project uses an existing concrete frame tower, the Dewitt-Chestnut Apartments, a 42 storey tower designed by SOM and built in 1966, as a base for comparison. The proposed structure uses a combination of solid timber products to make up the majority of the materials used, with steel reinforced concrete joints at areas of high stress. Cross-laminated timber panels compose the floor and span from the CLT shear wall core to the heavy timber columns on the perimeter. The perimeter floor plate connections are concrete link-beams to withstand wind pressure. The timber tower proposal is estimated to reduce the carbon footprint by 60-75% compared to a steel and concrete tower while maintaining an open floor plan for future use.¹

¹ "The Timber Tower Research Project: Re-imagining the Skyscraper," last modified June 6, 2013, <http://www.archdaily.com/?p=384032>.

Fig. 4.31 (Facing top) Exterior view of Stantec office building on Spadina and Wellington, Toronto - example of adaptive reuse, formerly the McGregor Socks factory built in 1905 with heavy timber framing. Photo by Richard Johnson.
Fig. 4.32 (Facing bottom) View of office interior. Photo by Stantec.



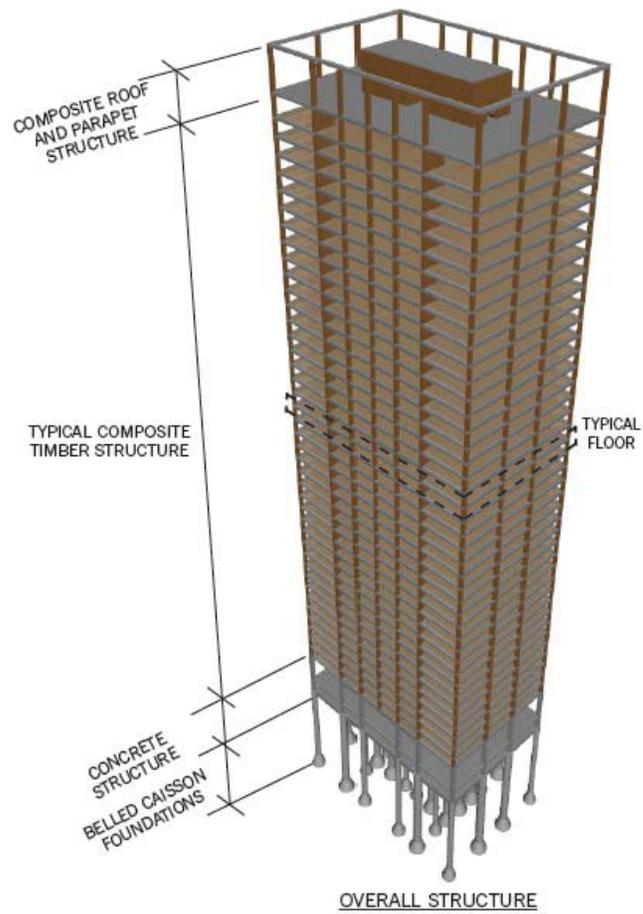
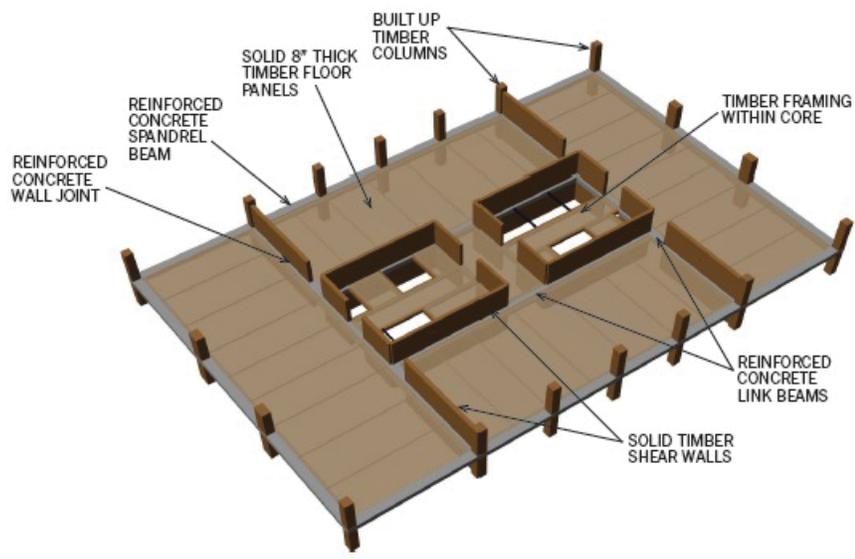


Fig. 4.33 SOM's Timber Tower Research Project, Chicago. Drawing by SOM.
Fig. 4.34 (Facing) Ibid.



TYPICAL FLOOR STRUCTURE

Cross-laminated Timber in Toronto

The recent pending change to the Ontario Building Code, allowing wood frame buildings of up to six storey's, has provided Toronto with a significant opportunity. As Europe continues to build six storey and higher cross-laminated timber and heavy timber frame buildings in their cities, we can begin to discuss how to increase density within Toronto. Infill sites are an ideal area for development using cross-laminated timber.

Observing infill sites throughout North American cities, the shape and area largely depend on how specific surveys divided large areas of land into blocks and then into smaller lots to sell. This may have been influenced by manufacturing, commercial, or residential zoning, as well as by land speculation, or by design.

Current development in cities is aimed at large empty or underdeveloped lots, where developers are able to profit most. Infill development, often on unusual or difficult sites, is becoming more promising, but it is not as lucrative to a developer.

I am looking into the standard residential lot as a means of increasing density while maintaining a strong community. In Toronto, with residential blocks divided up into narrow parcels of land, typically about 7 meters (25 feet) by 30 meters (100 feet), most developers are looking to acquire corner sites or multiple lots adjacent to each other. This is mainly because of the initial investment in building a core with elevators and a fire stair, and providing adequate daylight into each unit; with narrow lots there is only two faces for window placements.

Toronto has many existing structures on these lots, usually with a two to four storey brick or stucco facade. As the downtown core of Toronto rapidly builds high-rise condominiums on former parking lots or where vacant factories once stood, the narrow lots of smaller neighborhoods provides a competitive living alternative.

This study examines the potential for using cross-laminated timber on infill sites in Toronto. The preliminary massing and construction strategies, provides an overview for developing such sites. The cost breakdown shows a realistic option for financing the case study.

Fig. 4.35 (Facing) Diagram of Toronto's west end neighborhood with potential infill sites. Diagram by author.



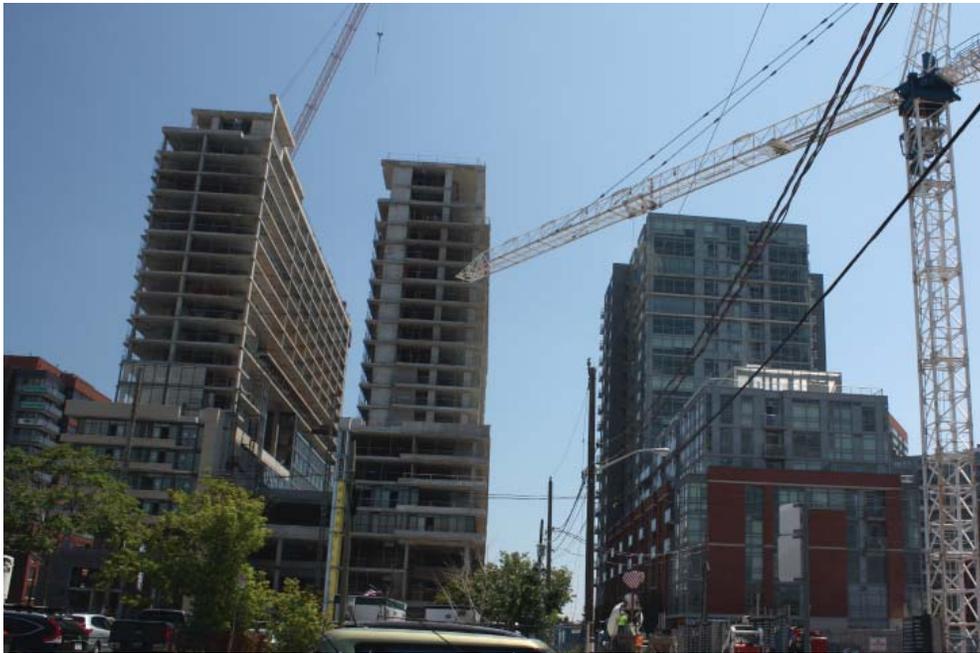


Fig. 4.36 West Queen West Triangle developments in former parking lot. Photo by author.

Fig. 4.37 (Facing top right) Panoramic view of triangle site at 24 Howard Park Ave. with existing auto repair shop. Photo by author.

Fig. 4.38 (Facing bottom right) Proposed Howard Park Condos by Raw Architects. Rendering by Raw Architects.



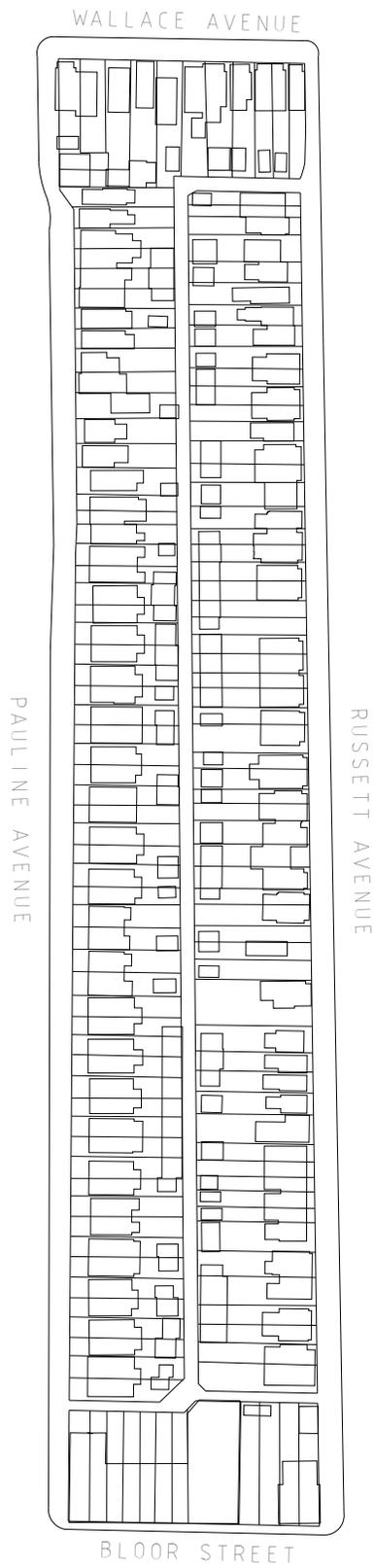
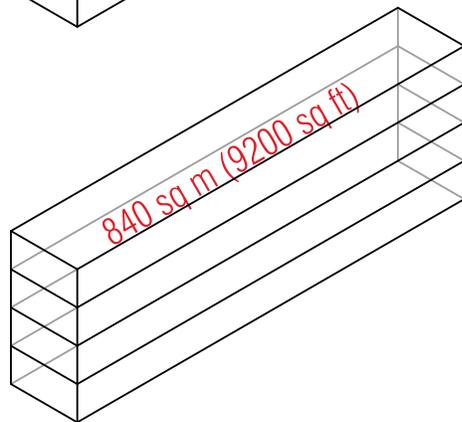
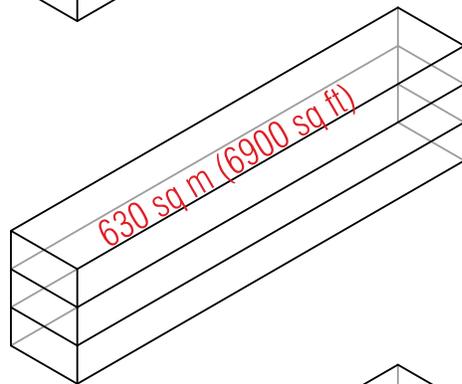
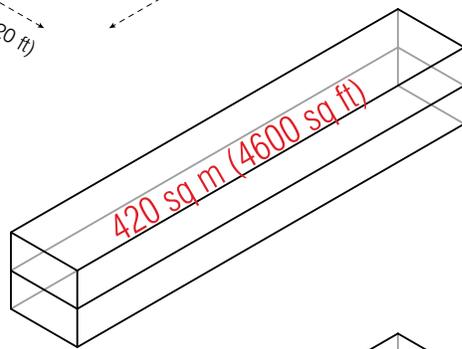
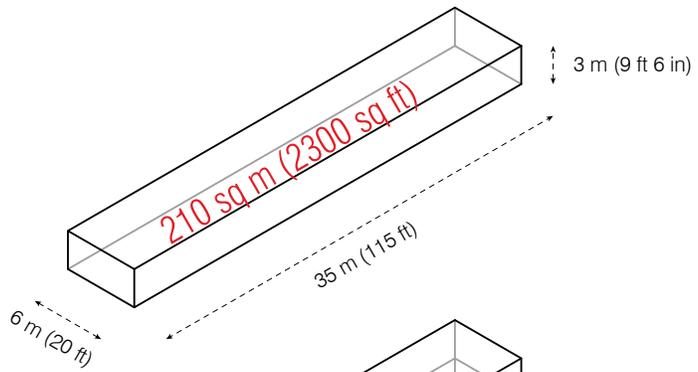


Fig. 4.39 Typical Toronto residential block with subdivided narrow lots. Diagram by author.

Fig. 4.40 (Facing) Narrow lot total area for one to four story building. Diagram by author.



CASE STUDY DEVELOPMENT

Example from Multiple Listings Service and Realtor.ca:

Location: 1079 Bathurst Street (south of Dupont)

Lot Size: 28 ft wide by 105 ft deep (2940 sq ft)

Price: \$749,000 (\$255 per sq ft for vacant lot)

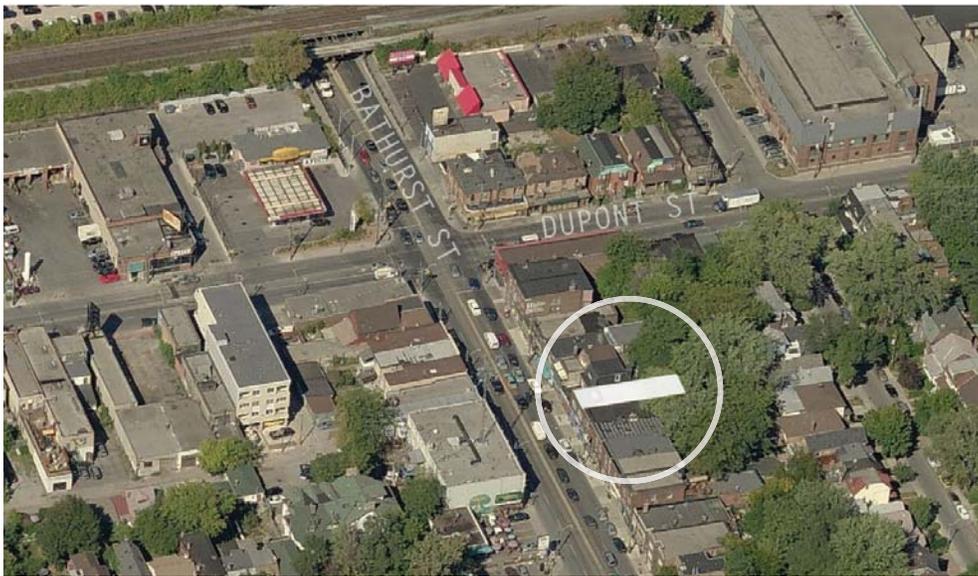




Fig. 4.41 (Facing top). Aerial view of site and surroundings. Photo by Bing Maps.

Fig. 4.42 (Facing bottom) View of site looking north along Bathurst St towards Dupont. Photo by author.

Fig. 4.43 View of site with height massing. Drawing by author.

Massing and Iterations

I chose a property listing on realtor.ca in order to have a realistic acquisition price for the particular neighborhood. The site, 1079 Bathurst Street, listed in the fall of 2013 as an empty lot, 28 feet wide by 105 feet deep for 2,940 square feet total, selling for \$749,000. It was formerly a 2 storey commercial brick building that burned down. The current property owner is selling the lot as a potential development site.

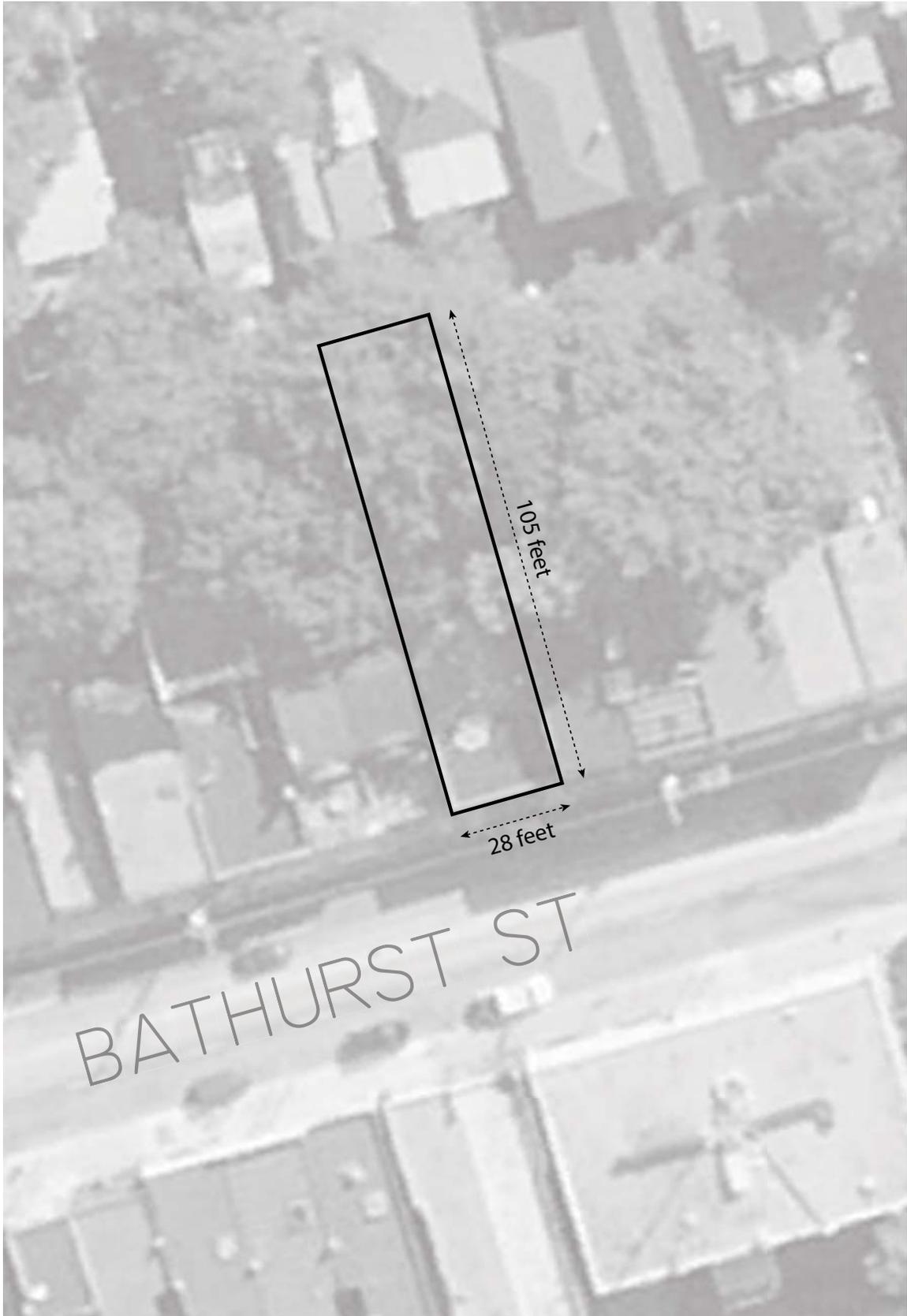
Speculative projects, such as this, will come with unforeseen factors, such as underground site conditions, community opposition to demolition of an existing structure, and to mid-rise development in a typically two to four storey neighborhood. Finding a balance between high-quality living spaces, height restrictions based on daylight accessibility in the neighborhood, and development incentives must be addressed.

My initial design sketches for the site responded to the *Avenues & Mid-Rise Buildings Study*, a document commissioned by the Toronto City Planning Division in 2010. The goal of the report was to evaluate how Toronto could increase density by building mid-rise (five to eleven storeys) buildings on the avenues. The authors, a team of architecture and urban design firms, estimate that if half of the potential properties on Toronto's avenues are developed with mid-rise buildings over the next twenty years, they can provide for approximately 250,000 new residents. The report provides guidelines for determining the height and setbacks for each building in order to minimize shadows to the surrounding area.¹

The massing studies I developed for the 1079 Bathurst site (figure 5.48) are intended to start a discussion for developing these types of narrow lots using cross-laminated timber. The potential for cross-laminated timber to accommodate design flexibility—fast construction period, lighter material compared to concrete and steel, large spans for open floors plans—and the Ontario Building Code currently accommodating for mid-rise timber buildings, is a great opportunity for Toronto to increase environmentally responsible housing.

1 “Avenues & Mid-Rise Buildings Study,” last modified May, 2010, <http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=7238036318061410VgnVCM10000071d60f89RCRD>.

Fig. 4.44 (Facing) Site diagram of site.
Drawing by author.



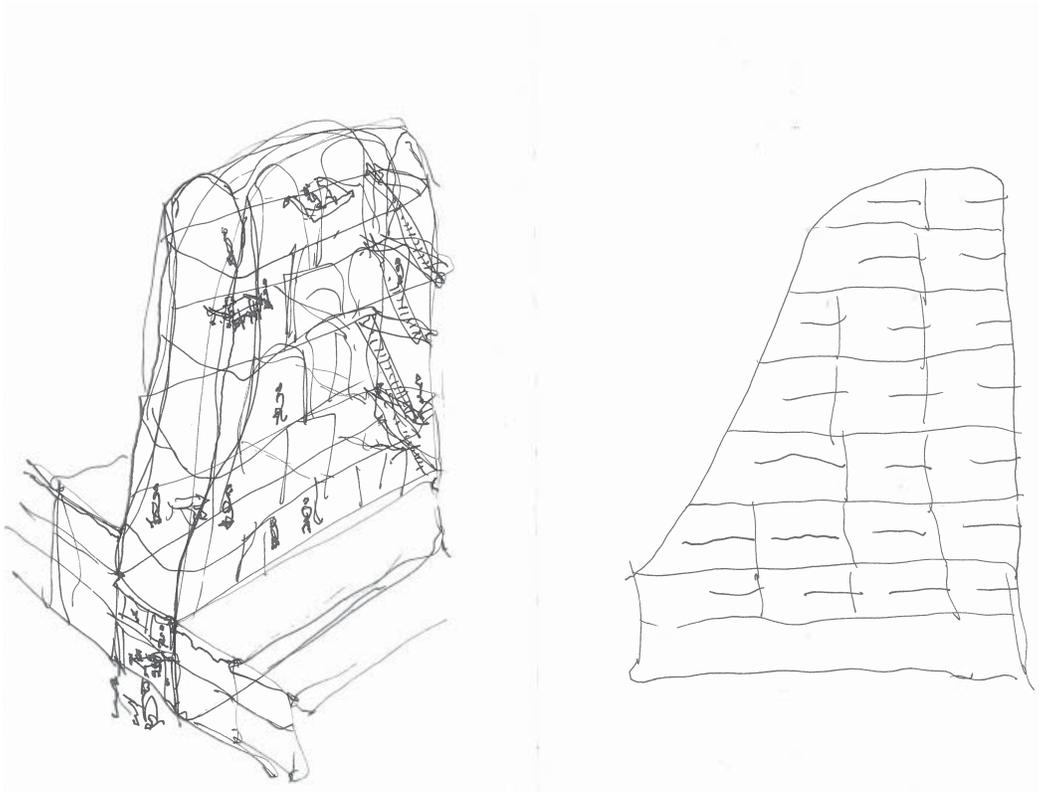
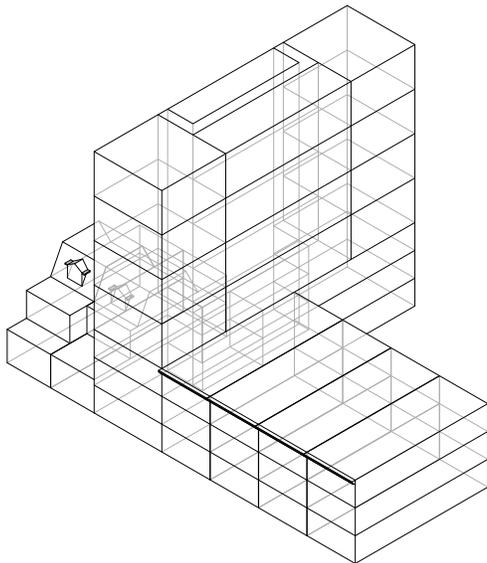
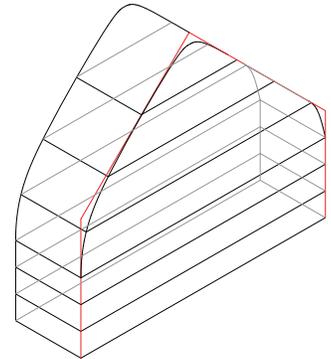
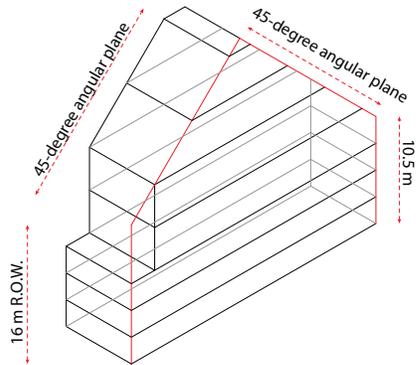
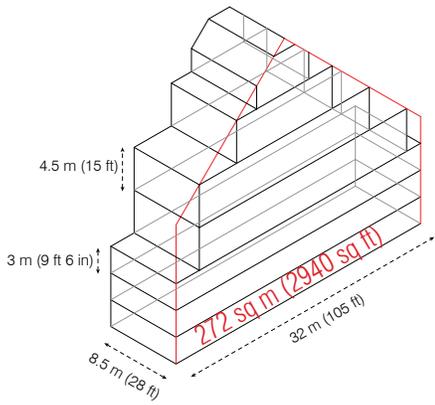
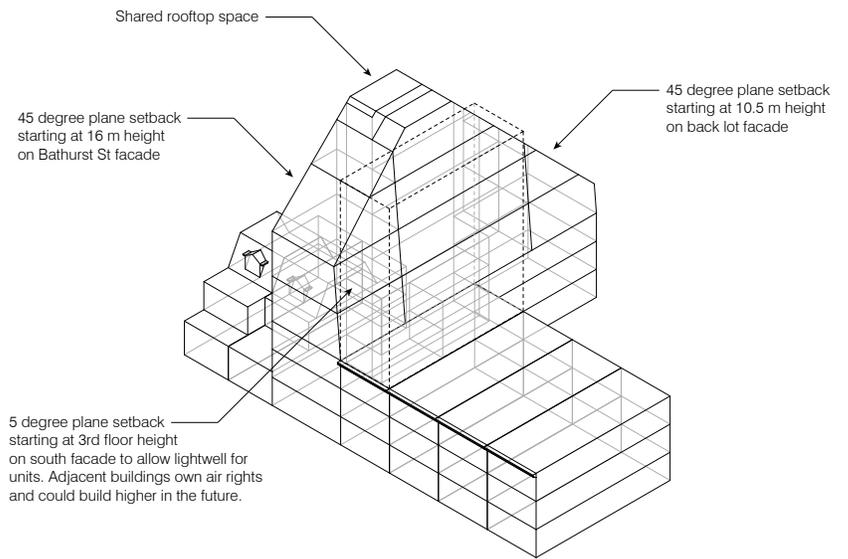


Fig. 4.45 Sketches of massing and residential units. Drawing by author.

Fig. 4.46 (Facing) Massing diagrams based on guidelines from the *Avenues & Mid-rise Buildings Study*, Toronto. Drawing by author.



MAXIMUM STACKED PROGRAM



PROGRAM WITH MID-RISE GUIDELINE SETBACKS AND LIGHTWELL

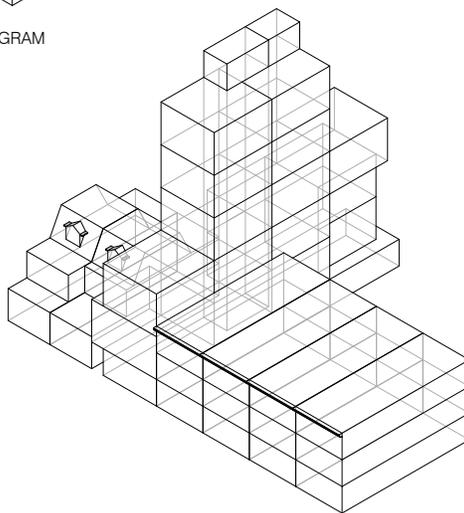


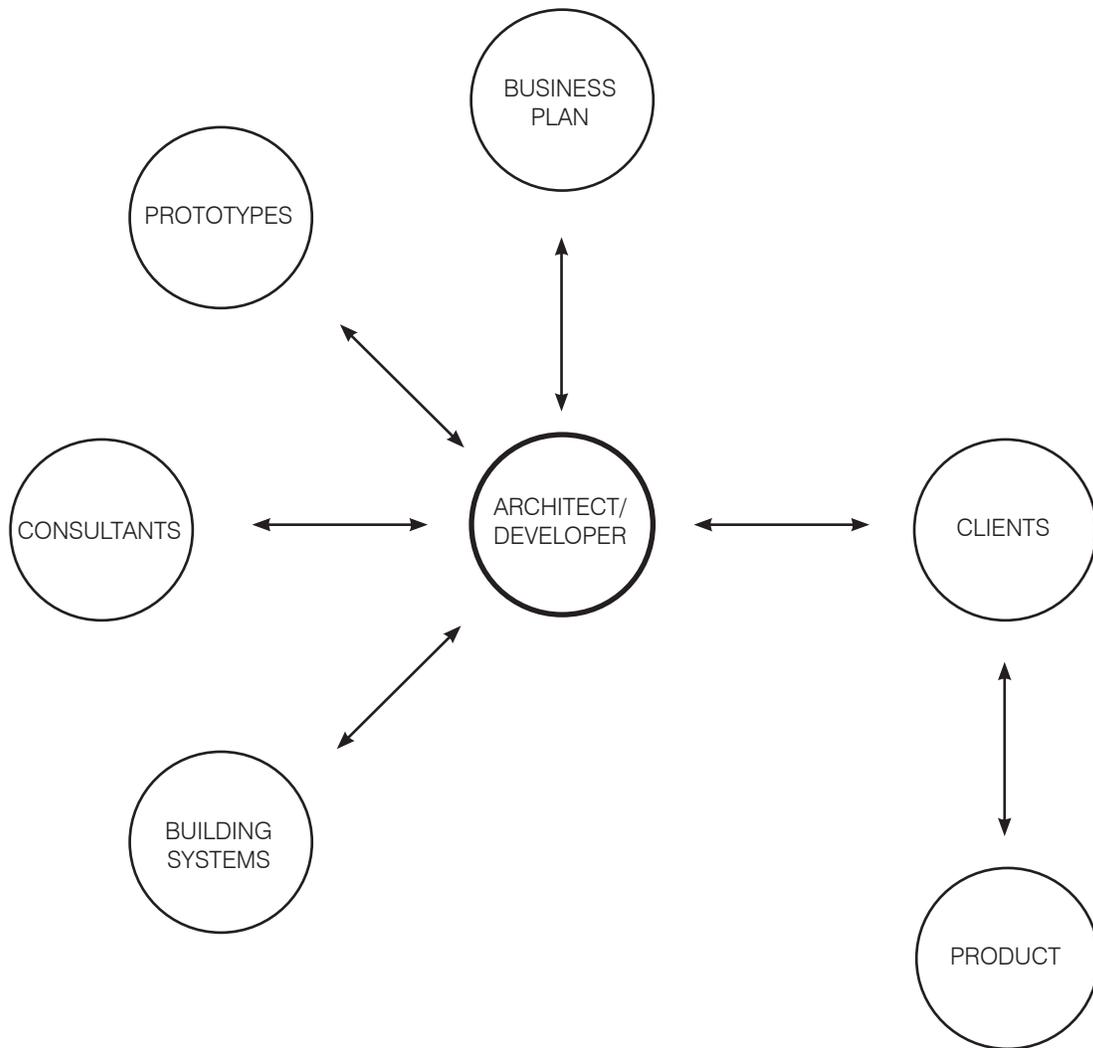


Fig. 4.47 CLT panels assembled on-site by crane. Photo by KLH UK.

Fig. 4.48 (Facing top) CLT panels assembled into modules for BMW Ammerwald Hotel in Tyrol by Oskar Leo Kaufmann. Photo by Adolf Bereuter.

Fig. 4.49 (Facing bottom) Hotel room modules assembled on-site. Photo by *ibid.*





Project Economics and Cost Breakdown

The economics of a building project proposal are important to examine, developing all of the costs associated with building. The 1079 Bathurst Development pro forma is broken down into six main categories; property acquisition cost, hard costs, soft costs, sales, loan formula, and rate of return. The proposal shows how one might approach developing a site within a realistic framework.

The 1079 Bathurst site is relatively costly at \$749K, however it is located in a central downtown area with the Dupont subway station a couple of blocks away. With a total site square footage of 2940, the cost per square foot comes to \$255. The hard costs are broken down into the site excavations and foundations and the concrete core as traditional construction methods while the cross-laminated timber panels are slightly more expensive due to the new construction technique and transportation costs. From a pure price perspective, using cross-laminated timber is not the most cost effective compared to standard wood framing but is competitive to concrete and steel. If the market demands more cross-laminated timber and engineered timber in Toronto, manufacturing facilities will open in Ontario, potentially allowing the price to be more competitive because of lower transportation costs.

The sales of the units are competitive for the new build units in the surrounding area with a \$720 per square foot cost. One of the disadvantages to building on small infill lots is the ratio of initial investment to total square footage. With a proposed 14 total units coming to a total gross square footage of 8,580, the rate of return is not as high compared to a larger site. However, because the prefabricated cross-laminated timber panels require less on-site construction time, the total labor construction cost decreases. In the long term, the initial investment would become less risky and development on narrow lot sites would be streamlined.

Fig. 4.50 (Facing) Integrated business plan diagram with architect/developer working with clients. Drawing by author.

TORONTO PRO FORMA BASED ON NEW BUILD		
1070 Bathurst Street Toronto, Ontario M5R 1W5 †		
ACQUISITION		COST
PURCHASE COST	2940	\$749,000.00
PER SQFT	\$254.76	
APPRAISAL / ENVIRONMENTAL FEES		\$1,000.00
SURVEY		\$2,000.00
ONTARIO AND TORONTOLAND TRANSFER TAX WITH REBATES		\$15,635.00
TITLE INSURANCE		\$300.00
HST	13.00%	\$48,685.00
BORROWERS LEGAL FEES		\$5,000.00
INSPECTION		\$600.00
INTEREST CARRYING COST (12MOS) (1)	5.00%	\$18,725.00
TOTAL ACQUISITION COSTS		\$840,945.00
HARD COSTS	SQUARE FT	COST
CONCRETE		
SITE EXCAVATION AND CONCRETE FOUNDATIONS AT \$180/SQFT	2900	\$522,000.00
CONCRETE CORE AT \$150/SQFT	835	\$1,002,000.00
CROSS-LAMINATED TIMBER		
L1 COMMERCIAL AND SHARED RESIDENTIAL AT \$180/SQFT	1960	\$352,800.00
L2-3 RESIDENTIAL AT \$200/SQFT	1,586	\$634,400.00
L4-7 RESIDENTIAL AT \$200/SQFT	1352	\$1,081,600.00
L8 SHARED ROOF MODULE AT \$200/SQFT	450	\$90,000.00
L8 ROOF LANDSCAPING AT \$40/SQFT	780	\$31,200.00
SUB-TOTAL HARD COST		\$3,714,000.00
CONTINGENCY (4)	18%	\$668,520.00
TOTAL HARD COST		\$4,382,520.00
SOFT COSTS		
INSURANCE		\$5,000.00
BUILDERS RISK INSURANCE		\$10,000.00
ARCHITECT OF RECORD	8%	\$350,601.60
ENGINEER	2%	\$87,650.40
PERMITS & FEES		\$5,000.00
ZONING ARCHITECT (5)		\$3,000.00
ZONING ATTORNEY (5)		\$4,000.00
CONTROL INSPECTION ENGINEER		\$1,500.00
LLC - LEGAL FEES		\$2,000.00
LLC - REGISTRATION		\$2,000.00
INTEREST - CONSTRUCTION LOAN (2)	12MOS	\$219,126.00
MARKETING / BROKERAGE	1%	\$6,898.78
CONTINGENCY (3)	5%	\$34,493.90
TOTAL SOFT COSTS		\$731,270.68

SALES		
RESIDENTIAL - GROSS SQ.FT. (7)		8,580
LOSS FACTOR - SQ.FT.	10%	858
RESIDENTIAL - NET SQ.FT.		7,722
RESIDENTIAL - SELLING NET	\$720/SQFT - 1BR & STUDIO UNITS	\$5,559,840.00
COMMERCIAL - SELLING NET	\$500/SQFT - 1 UNIT COMMERCIAL RAW	\$980,000.00
TOTAL SALES		\$6,539,840.00
SUB-TOTAL PROJECT COST		\$5,954,735.68
TOTAL VALUE OF PROJECT		
NET PROFIT BEFORE TAXES		\$585,104.32
TOTAL RATE OF RETURN PER PROJECT		9.83%
PROPERTY AQUISITION & CONSTRUCTION LOAN FORMULA		
HARD COSTS		
SOFT COSTS		
TOTAL CONSTRUCTION LOAN (HARD+SOFT)		\$5,113,790.68
TOTAL LAND COST VALUE MORTGAGE		\$840,945.00
TOTAL CREDIT		\$5,954,735.68
DOWN PAYMENT ON HARD AND SOFT COSTS	20%	\$1,022,758.14
DOWN PAYMENT ON AQUISITION + AQUISITION SOFT COST:	25%	\$210,236.25
TOTAL MICRO-CREDITORS FOR DOWN PAYMENTS		\$1,232,994.39
DIVIDENDS & RATE / RETURN		TOTAL
TOTAL PROFITS		\$585,104.32
DEVELOPER PROFIT 70%		\$409,573.02
MICRO-CREDITORS PROFIT 30%		\$175,531.30
TOTAL BANK CREDIT REPAYMENT		\$4,721,741.29
TOTAL MICRO-CREDIT REPAYMENT		\$1,408,525.68
MICRO-CREDITORS RATE OF RETURN	$\frac{(\$1,408,525.68 - \$1,232,994.39)}{\$1,232,994.39}$	14.24%

Fig. 4.51 1079 Bathurst Street development pro forma with site acquisition and cost breakdown. Document by author.

Moving Forward - Twigsort Application

This thesis argues for using one material and, in turn, considers a number of essential factors in the architecture and construction process. Knowing how we transform raw materials and resources into building products and materials, enlightens us as we shape our built environment. Throughout this process—researching various materials and processes, design methodologies, and parties involved—I wanted to know more about what materials our buildings are made from and what other new products are being discussed in the industry as environmentally responsible.

Curious to find out about the other side of the building industry, I went to the Construct Canada trade show, one of the largest building material trade shows in North America. I also attended the Toronto Wood Solutions Fair on engineered timber. Both conferences were held at the Metro Convention Centre in Toronto.

Questions on material sourcing led me to collaborate with fellow M.Arch students Saeran Vasanthakumar and Mark Tam, and alumni Andrea Hunniford, to design *Twigsort*, a website database that bridges the highly fragmented design, specification, and construction workflow for architects and interior designers. The idea is simple: replace binder and catalogue libraries with a firm-specific, digital material database. The designer can search for a material or more specific product and compare different factors including manufacturer location, cost, and certifications. The material supplier benefits by attracting more potential customers and is able to update their information without wasting tons of paper and money on new binders. With extensive research we noticed the frustrations and demands during the specifications process.

As the workflow continues to move to a digital cloud collaboration between companies, not only in the architecture and construction field, but in many other disciplines, creating and maintaining a material database will be essential to the process. Building information Modeling (BIM) and web applications that allow construction workers, architects, and engineers to connect using social media and view background material data, such as PlanGrid, Fieldlens, and Sourcemap will have a major impact on the future of the industry.

Fig. 4.52 (Facing) Screenshot of Twigsort Material Database prototype website. Photo by Twigsort.

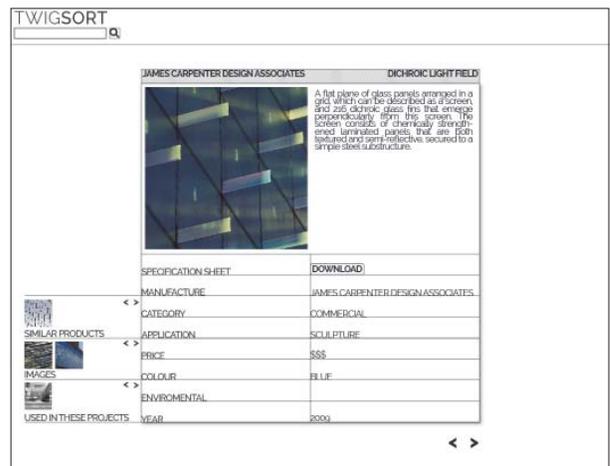
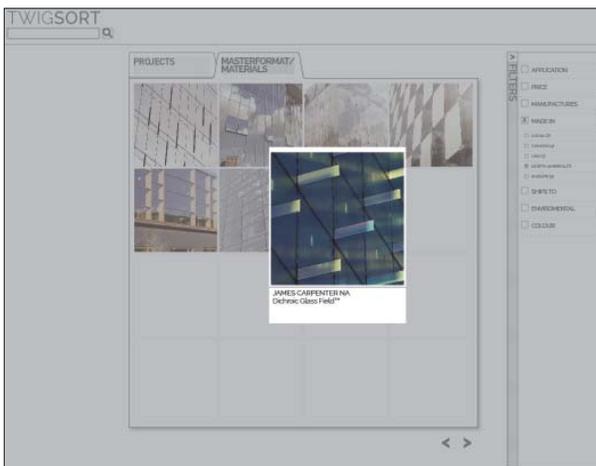
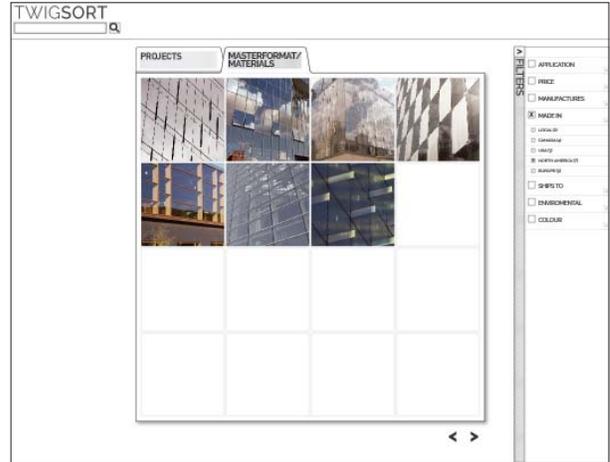
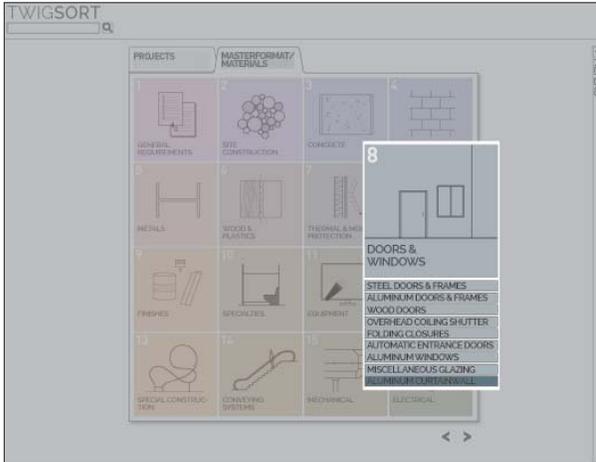
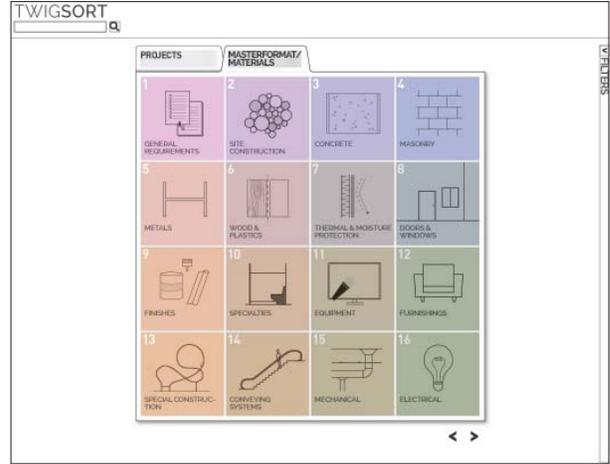
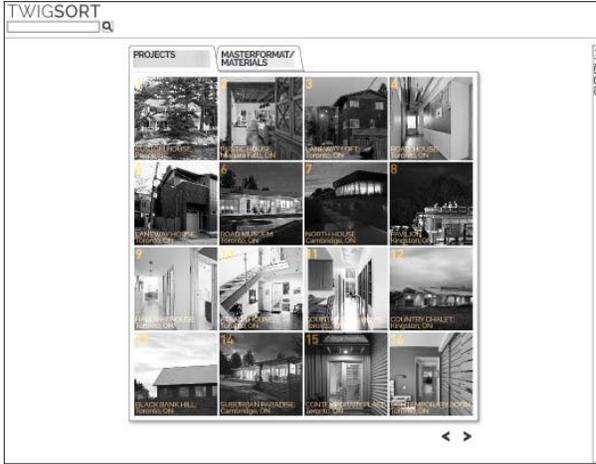




Fig. 4.53 Weathered timber post and metal bolt. Photo by author.

They [animals] seek the scent of previous occupants. For that reason I believe that the primary quality which makes the built environment tactile is evidence that people have participated in its construction. It is for that reason, when I think of the alienation which exists today between people and the built environment, that I put it down primarily to the all-pervasive and essentially sterile role of industry, which suggests that decisions about this environment were made not by people but by the needs of industry.

- Peter Rice, *An Engineer Imagines*, 1998. 78.



Fig. 4.54 (Left) Ontario coniferous forest.
Photo by Paul Henman.

Fig. 4.55 (Right) 5-Ply CLT Panel. Photo by
Naturally Wood.

Fig. 4.56 (Facing) Interior of Hunsett Mill
house in Norfolk, England by ACME. Photo
by Cristobal Palma.



Conclusion

The state of the architecture and construction industry is at an incredibly interesting time. There is a vast amount of information and data-rich material constantly shared and updated on the internet, environmental and data simulation are becoming more accurate in Building Information Modeling, and fabrication methods, such as 3d printing and robotic arms for CNC machining and assembly are becoming more sophisticated. It is difficult to predict how these new technologies can be applied to large scale developments because new building projects are just beginning to use them. And the environmental impact and performance of a material and building, with all of its heated political and economic debate, will be the driving force in the twenty-first century.

This thesis brought me closer to understanding the many processes in architecture by using cross-laminated timber as a catalyst. Comparing the three materials—cross-laminated timber, concrete, and steel—gives us a background to how we shape these materials into our buildings and cities. Each section, *Environmental Performance, Ease of Manufacture, Organized Assembly, and Design Flexibility* encompasses technical, historical, and design issues, making an accurate assessment for each material. Cross-laminated timber is a simple innovation, standard lumber oriented and glued in crisscross layers to form a solid timber panel. These types of material developments have significant effects to how we design and build. They provide architects and clients with the only renewable structural material we have. And timber connects its inhabitants to a warm and tactile beauty used since the beginning of architecture.



Fig. 4.57 Rings of tree trunk. Photo by author.

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