Burning Up: Fire Safety Barriers to Low Embodied Carbon Housing in the NBCC

by

Maxwell Perry

A thesis
presented to the University Of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Architecture

Waterloo, Ontario, Canada, 2024

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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 final revisions as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The National Building Code of Canada (NBCC) emerged in response to, and developed from, catastrophic conflagrations throughout history which demanded the need for consistent construction and fire safety standards for buildings across the country. While fire safety remains an essential consideration in the development of Canadian society, many Code requirements inadvertently prescribe construction with high embodied carbon – emissions arising from the production, maintenance, and disposal of building materials – failing to recognize climate change as an existential threat. This thesis identifies, quantifies, and proposes alternatives to fire safety regulations within Part 3 of the NBCC that impede the design of low embodied carbon housing, particularly in missing middle and mid-rise typologies. While removing these regulatory barriers will not directly reduce embodied carbon, it enables future construction to have lower embodied carbon emissions which is critical to addressing Canada's ongoing climate and housing crises.

Significant emissions reductions must occur in order to keep global temperatures from rising above +2°C and avoid climate catastrophe. Embodied carbon contributes approximately 13% of Canadian emissions and is essential to address, especially as operational carbon decreases with decarbonized energy and greater insulation. Missing middle and mid-rise housing offer the opportunity to provide low embodied carbon housing, however current NBCC regulations inhibit these benefits by prescribing urban, formal, and material requirements that are more restrictive than necessary.

The contemporary version of the NBCC is the result of continuous incremental development which reflects historical perspectives, scientific research, shifting social values, and arbitrary adjustments that can trace its roots back to the London fire of 1087. Construction materials, fire detection and suppression, and occupant behaviour have shifted significantly since the underlying structure of the building code was written. This work analyzes the Code as not only a technical document, but also as a historical and political artifact, emphasizing the importance of reconsidering regulatory assumptions in light of current fire safety and climate goals. Critically, the Code must explicitly include embodied carbon as one of its objectives.

Part 3 of the NBCC, which governs fire protection, accessibility, and safety, holds the potential to significantly reduce embodied carbon both through the amelioration of its explicit barriers, and through its influence on holistic design decisions. Seven barriers to low carbon housing at the urban, building, and material scale are identified through literature and expert interviews. Furter, their impact on fire safety and embodied carbon is analyzed, resulting in proposed changes which range from specific Code amendments to broad directions for future development.

The findings demonstrate that there are significant opportunities to align NBCC regulations with low embodied carbon goals without compromising fire safety. While the list of barriers investigated is inexhaustive, the breadth serves to illustrate the persistent manner that the Code specifies high embodied carbon while defining which changes are most impactful in emissions reduction. They provide starting points for more focused research and offer a framework through which to critically evaluate the Code. The work encourages architects and associated professionals to view the NBCC as a malleable document and advocates for greater involvement in future editions. Further, this thesis makes a unique contribution by identifying the relationship between fire safety and embodied carbon and by addressing their potential interactions through quantifiable metrics.

Acknowledgements

First and foremost, I must thank the community at the University of Waterloo School of Architecture. Through the last six years, the school has fundamentally changed the way I see the world, opening up a series of difficult and productive endeavours. It has been an honour to be surrounded by such an inspiring group of peers, professors, and faculty. Thank you to every one of my classmates, teachers, TAs, mentors, and students. It has been my privilege to conduct the work for this thesis on the traditional lands of the Neutral, Anishinaabeg, and Haudenosaunee peoples. My studio, the School of Architecture, and the University of Waterloo are situated on the Haldimand Tract, land granted to the Six Nations that includes six miles (9.66 km) on either side of the Grand River, from its source to mouth.

I am immensely grateful to my co-supervisors, Lola Sheppard and John Straube, for their guidance, insight, and mentorship. Your expertise, thoughtful feedback, and immense wealth of knowledge have been instrumental throughout this process. You were both integral parts of my undergraduate education as well, whose teachings has shaped my work fundamentally. John and Lola have kept my opinions measured, and grounded, while encouraging me to push boundaries with keen insights every conversation.

Mohamad Araji and Jane Hutton have both helped advance this work throughout the past year. Their constructive feedback from the start of this process helped me narrow my focus while maintaining consideration for a broad range of topics. Jane's support, questions, and encouragement formed much of the early research and direction for this thesis, while Mohamad, also a committee member, helped hone in on the consequences and potentials of the research.

I also want to extend my thanks to the experts who have generously shared their time, knowledge, and experience. Beth Weckman, also the internal reader, was invaluable in sharing her perspectives on fire safety and testing. Keith Calder's research on the development of the building code was essential; without it, this thesis may not have been possible. Shoshanna Saxe and her work on quantifying embodied carbon in the built environment has been formative. Conrad Speckert's perspective on the importance of the building code and its ability to shape architecture provided the foundation from which this thesis was built. Your willingness to engage in

conversation and the candor with which you share your knowledge have been particularly helpful.

Thank you to Jason Cai, Owen Melisek, Eva Sabourin, Serena Valles, Catherine Zheng, Emily Li, and Aidan Tyrrell. Your friendship has meant the world to me; your kind words eased my burdens and your critical words moved me forward.

To my parents, Cynthia and Jason Perry, your unwavering support has meant the world to me.

To Berlin Pang, thank you for your patience, understanding, and endless encouragement. Your belief in me means more than words can express.

Finally, I would like to thank the financial supporters, without whom this project would have been possible, but certainly more difficult. Generous scholarships from the Social Sciences and Humanities Research Council, the Faculty of Engineering at the University of Waterloo, and the University of Waterloo School of Architecture have enabled this work. I hope this thesis allows me the privilege to do more and better work in the future.

Dedication

This thesis is dedicated to all who have worked tirelessly to develop the NBCC and to all that continue this work to ensure the safety, health, accessibility, and sustainability in our built environment. Your work shapes the future of architecture in Canada.

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Part One: Embodied Carbon and our Burning House

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1.02 Canadian and global GHG emissions by sector. Approximately 39% of building material emissions are the result of residential construction in Canada, followed by 20% from non-residential buildings, 17% from oil and gas construction, and 14% from infrastructure. Author's drawing informed by: Leopold Wambersie and Claudiane Ouellet-Plamondon, "Developing a Comprehensive Account of Embodied Emissions within the Canadian Construction Sector," Journal of Industrial Ecology, September 27, 2024, https://doi.org/10.1111/jiec.13548; Architecture 2030, "Why The Built Environment," Architecture 2030, accessed October 24, 2024, https://www.architecture2030.org/why-the-built-environment/.

1.03 Per capita embodied carbon emissions from the construction sector by country. Although only 13% of Canada's emissions are from the construction sector, the total emissions are 87 MtCO2e. Author's drawing informed by: Leopold Wambersie and Claudiane Ouellet-Plamondon, "Developing a Comprehensive Account of Embodied Emissions within the Canadian Construction Sector," Journal of Industrial Ecology, September 27, 2024, https://doi.org/10.1111/jiec.13548; Lizhen Huang et al., "Carbon Emission of Global Construction Sector," Renewable and Sustainable Energy Reviews 81 (January 1, 2018): 1906–16, https://doi.org/10.1016/j.rser.2017.06.001.

1.04 Cumulative emissions from a high performance building comparing embodied carbon and operational carbon based on city location. Provinces with low carbon electricity grids like British Columbia, Ontario, Quebec, and Newfoundland and Labrador show that emissions are dominated by embodied carbon. In high carbon electricity provinces like Nova Scotia and Alberta, even though over the whole life operational

carbon exceeds embodied carbon significantly under current scenarios, decarbonization is coming. Author's drawing informed by: CAGBC, "Embodied Carbon: A Primer for Buildings in Canada" (Ottawa, ON: Canada Green Building Council, Forestry Innovation Investment Ltd., March 2022).

1.05 Total interior living space required to house Canada's growing population through 2050 compared to the area of the City of Toronto. Research suggests that although Canada will not grow at the same rate as the global average though 2050, it will exceed the global average by 2060 which suggests Canada will need significant new construction long into the future. Author's drawing informed by: Sylvia Marinova et al., "Global Construction Materials Database and Stock Analysis of Residential Buildings between 1970-2050," Journal of Cleaner Production 247 (February 20, 2020): 119146, https://doi.org/10.1016/j.jclepro.2019.119146.

1.06 Life cycle assessment stages and component phases. Phases B8 and B9 are often only included in infrastructure projects and aim to account for the carbon emitted through the utilization of a roadway by cars for example. These phases offer a theoretical appraoch to quantifying the lifestyle that a building supports. Author's drawing.

1.07 Embodied carbon flowchart for timber products. Author's drawing informed by: Emily Newmarch, "Embodied Carbon: Embodied Carbon," in Modern Apartment Design (Routledge, 2021).

1.08 Simplified embodied carbon flowchart for steel products. Author's drawing informed by: Emily Newmarch, "Embodied Carbon: Embodied Carbon," in Modern Apartment Design (Routledge, 2021).

1.09 Simplified embodied carbon flowchart for concrete. Author's drawing informed by: Emily Newmarch, "Embodied Carbon: Embodied Carbon," in Modern Apartment Design (Routledge, 2021).

1.10 Missing middle and mid-rise typologies. It is important to note that definitions for both missing middle and mid-rise vary by publication and that the forms identified in the diagram refer to the typologies that are focused on in this thesis. Author's drawing.

1.11 Overview of embodied carbon intensities of housing typologies and embodied carbon limits. Although fairly subtle, there is a clear trend of increasing embodied carbon with increasing height. Author's drawing.

1.12 Measurement units for embodied carbon. Each measurement unit has distinct advantages and disadvantages however embodied carbon intensity is used by the overwhelming majority of policies and literature. Author's drawing.

1.13 Map of nationally enacted embodied carbon policy. The literature used to create this map has a distinct lack of data on the global south. This omission is not meant to suggest that there are no embodied carbon policies planned or in action. Author's drawing informed by: see text for references; "CLF Embodied Carbon Policy Tracking Map," Carbon Leadership Forum, May 1, 2024, https://carbonleadershipforum.org/clf-policy-toolkit/.

1.14 RAIC phases of an architecture project with the NBCC as the underlying design ethos of Canada. Low embodied carbon design currently only exists in the realm of the socially attractive (through client briefs) or through financial feasibility (through reduced cost). However, in both cases, these savings are apt to be lost unless the legal minimum includes embodied carbon considerations. Author's drawing.

Part Two: The National Building Code of Canada

2.01 Flowchart of the application of the NBCC in Canada. Author's drawing.

2.02 High-level timeline of NBCC development. Author's drawing.

2.03 The historical roots of the NBCC. Based on the model codes published in the USA, the NBCC can trace its origins back to the 11th century. The history of the Code is a complex web of municipal building ordinances, insurance standards, key researchers, and significant fire events. Author's drawing.

2.04 Stele of the code of Hammurabi. unknown, Code de Hammurabi, Photograph, 225 x 79 x 47 cm, Musée du Louvre, accessed October 25, 2024, https://collections.louvre.fr/en/ark:/53355/cl010174436.

2.05 The great fire of Rome. Robert Hume, The Fire of Rome, 18 July 64 AD, 1785, Oil on Canvas, 76 x 93 cm, 1785, Musee des Beaux-Arts Andre Malraux, https://commons.wikimedia.org/wiki/

File:Robert,_Hubert_-_Incendie_%C3%A0_Rome_-.jpg.

2.06 Nero punishing the Christians (right) for supposedly setting the fire, which was the first instance in a long line of blaming marginalized people for city fires (see Mrs. O'Leary in the Chicago Fire). Henryk Siemiradzki, Nero's Torches (Christian Candlesticks), 1876, Oil on Canvas, 385 x 704 cm, 1876, National Museum in Kraków, https://commons.wikimedia.org/wiki/File:Siemiradski_Fackeln.jpg.

2.07 A broadside ballad which gives an account of the 1666 fire in London. J. Clark, The LONDONERS Lamentation, 1666, Print, 1666, EEBO, https://commons.wikimedia.org/wiki/File:Londoners-Lamentation.gif.

2.08 The cubic capacity of a building as defined by London Fire Brigade Chief James Braidwood. Note that although the dimensions of the building footprint could vary, the 60' height limit was the maximum height allowed. Author's drawing.

2.09 The cubic capacity concept as applied by the New York Board of Fire Underwriters to define the "standard building". It was above this theoretical building volume that additional fire safety measures were required and insurance premiums increased. Author's drawing.

2.10 View of Chicago after the fire in 1871. George N. Barnard, Untitled (Chicago after the Chicago Fire), 1871, Photograph, 1871, Art Institute of Chicago, https://commons.wikimedia.org/wiki/File:Attributed_to_George_N._Barnard_-_Untitled_(Chicago_after_the_Chicago_Fire)_-_Google_Art_Project.jpg.

2.11 View of Boston after the fire in 1872, an immense scale of destruction despite significant "fireproof" construction. John Adams Whipple, View from Corner of Washington & Bromfield Streets, 1872, Photograph, 1872, Boston Public Library, https://commons.wikimedia.org/wiki/File:Boston_Fire_from_Washington_%26_Bromfield_panoramic_by_Whipple,_1872.jpg.

2.12 The Triangle Shirtwaist Factory fire in the Asch Building (now the Brown Building) which still stands at 23-29 Washington Place. unknown, Triangle Shirtwaist Factory Fire First Published on Front Page of The New York World, March 25, 1911, Photograph, March 25, 1911, University of Cornell, https://commons.wikimedia.org/wiki/File:Image_of_Triangle_Shirtwaist_Factory_fire_on_March_25_-_1911.jpg.

2.13 A memorial of 100,000 people attended the funeral for the victims of the fire, leading to stronger labor laws, building regulations, and worker's unions. unknown, The Funeral Procession, April 5, 1911, Photograph, April 5, 1911, University of Missouri-Kansas City School of Law, https://famous-trials.com/trianglefire/966-images.

2.14 View of Hull-Ottawa fire blowing across the Ottawa river. unknown, Big Fire of April 26th 1900, April 26, 1900, Photograph, April 26, 1900, Bytown Museum, https://imgur.com/a/EOzrI44.

2.15 The aftermath of the Laurier Palace Theatre fire, relatively intact furnishings and structure show the dangers that egress and smoke pose in the event of a fire. unknown, The Aftermath of the Laurier Palace Theatre Fire, January 1927, Photograph, January 1927, Montreal Gazette Archives, https://montrealgazette.com/news/local-news/history-through-our-eyes/history-through-our-eyes-jan-9-1927-laurier-palace-theatre-fire.

2.16 Aftermath of the Toronto fire in 1904, many masonry exteriors of buildings remained standing although their interiors burned out. unknown, Aftermath of Fire, Wellington St, 1904, Photograph, 1904, Toronto Public Library Archive, https://digitalarchive.tpl.ca/objects/336780/fire-1904-aftermath-of-fire-wellington-st.

2.17 Survey responses from fire chiefs across the USA indicating recommended building heights and areas. Author's drawing reproduced from: Ira H. Woolson, "Allowable Heights and Areas for Factory Buildings," Transactions of the American Society of Mechanical Engineers 35 (January 1913): 231–37, https://doi.org/10.1115/1.4059921.

2.18 Height and area limits in the 1915 NBFU model code, it is interesting to note that a wood frame building with just one family is permitted to be 3 storeys in height, while those with two familys are only permitted to be 2.5 storeys in height, and those with more than two families must be fireproof. Excerpt from: National Board of Fire Underwriters, Building Code Recommended by the National Board of Fire Underwriters: An Ordinance Providing for Fire Limits, and Regulations Governing the Construction, Alteration, Equipment, Repair or Removal of Buildings or Structures (New York, NY, 1915), https://catalog.hathitrust.org/Record/100395166.

2.19 Height and Area Limit Comparison of the 1930 NBSFR and the 1941 NBCC. Author's drawing reproduced from: Keith Calder

and Peter Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada" (Sereca Consulting Inc, March 19, 2015).

2.20 The growth of allowable building areas as a result of changing units of measure. Holding all else equal, this simplified substitution to ease administrative burden increases fire risk by nearly 8%. It further shows the imprecision of defining building limits by simple whole numbers. Author's drawing.

2.21 Types of construction specified by building codes throughout time. Although the table does not correspond exactly with the graph below, the number of construction categories does not seem to have a significant role in reducing fire deaths. Further, the current construction types bear significant semblance to those in 1905 Author's drawing.

2.22 Number of fire deaths per capita and total number of fires in Canada from 1920 to 2005. Fire deaths and number of fires did not fall meaningfully after the introduction of noncombustible construction as a core tenet of the code. These outcomes only began to fall after the introduction of fire alarms in the 1977 NBCC, suggesting that noncombustibility does not play a large role in the safety of occupants. Author's drawing informed by: John Thomas, "The Use of Fire Statistics in Guiding Research and Code Development" (National Research Council of Canada, Fire Research Program, September 3, 2007).

2.23 Fundamental rules to determine building areas and heights proposed by R.S. Ferguson, a precursor to a performance code that was never to come. Excerpt from: Keith Calder and Peter Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada" (Sereca Consulting Inc, March 19, 2015).

2.24 Excerpts from NBCC 2020. Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), vi-1-18 Division A.

Part Three: Barriers to Low Embodied Carbon Housing

3.01 Excerpts from interview with Keith Calder on August 14, 2024. See Appendix A for full transcript

3.02 Excerpts from interview with Shoshanna Saxe on October 9, 2024.

See Appendix A for full transcript The distance is 21 m: Phineas Harper, “Edwardian Morals, Thatcher and Bad Design – Why Britain’s Homes Are so Hot,” The Guardian, July 20, 2022, sec. Opinion.

3.03 Excerpts from NBCC 2020. Canadian Commission on Building and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 3-102;103;244 Division B.

3.04 Minimum dimensions for an access route. These requirements form the basis for all new streets in Canada and represent a significant relationship between buildings and urban form. Author’s drawing informed by: Canadian Commission on Building and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 3-102;103;244 Division B.

3.05 Alternative methods of firefighter access for laneways in Toronto and Japan. Although these tactics hail from drastically different geographies, they employ similar strategies - right down to requiring an exterior strobe in some cases. Author’s drawing informed by: City of Toronto, “PH16.10 - Laneway Suites: Fire Access Requirements” (Toronto, ON: City of Toronto, September 8, 2020).; Kyoichi Kobayashi, “The History of Fires and Firefighting in Japan,” Fire Equipment and Safety Center of Japan, no. June-September 2022 (2022), https://www.kaigai-shobo.jp/fireserviceinjapan_eng.

3.06 Comparison of fire vehicle sizes in North America and Europe. European vehicles typically separate distinct functions and tools into different vehicles which allows for smaller and lighter trucks. An important advantage of the European vehicles is that as the wheel base of vehicles get shorter, the turning radius also decreases, allowing for access to tighter spaces. Author’s drawing informed by: Pierce Manufacturing Inc., “Aerials” (Oshkosh Corporation, March 2023), https://www.piercemfg.com/pierce/literature/aerials.; Magirus, “Fire Engines,” Magirus Group, accessed October 28, 2024, https://www.magirusgroup.com/de/products/fire-engines/.

3.07 Road width by country between 1987 and 2014. Note that these values are average road widths, including multi-lane roads and highways. Minimum road widths required for emergency access are likely more narrow than presented values. Although

the age of cities in Europe tends to be used as an argument for their narrow roads, the range presented represents broadly contemporary development. Only data from Europe, Japan, and Commonwealth countries was selected from the source dataset due to relatively similar regulatory systems. Austria, Canada, New Zealand, and the United States are grouped together as they are all land rich countries. There is a clear relationship between the average width and the percentage of roads less than 4 meters. Author’s drawing informed by: Shlomo Angel et al., “Blocks and Roads” (Atlas of Urban Expansion, 2016), http://atlasofurbanexpansion.org/data.

3.08 Total road area in the City of Toronto. The road coverage in Toronto has an embodied carbon of 59.0 MtCO2e. Vancouver, Montreal, and Calgary, have 27.7, 48.7, and 27.8 MtCO2e respectively. Author’s drawing informed by: Statistics Canada, “The Changing Landscape of Canadian Metropolitan Areas,” Human Activity and the Environment (Statistics Canada, June 28, 2016).

3.09 Embodied carbon of roadway paving used in Canada. Local road designs account for 2500 annual average daily traffic (AADT) while the arterial designs account for 75,000 AADT. The City of Toronto uses a predominantly hybrid approach to road paving. Author’s drawing informed by: Toronto Transportation Services, “Pavement Design and Rehabilitation Guideline, Second Edition” (City of Toronto, 2019).; City of Toronto, Applied Research Associates Inc., “Structural Pavement Design Guidelines” (City of Toronto, December 14, 2006).; EPDs via One Click LCA, “LCA & EPDs for Construction & Manufacturing,” One Click LCA, https://oneclicklca.com.

3.10 Comparison of current and proposed access route width relative to the embodied carbon of a building. The drawing assumes a building of 450 m2 with an embodied carbon intensity of 375 kgCO2e/m2 and a lifespan of 60 years. Paving emissions use values for the arterial hybrid and a typical lifespan of 30 years. Author’s drawing informed by: City of Toronto, “Sidewalks & Roads,” City of Toronto (City of Toronto, November 17, 2017), Toronto, Ontario, Canada, https://www.toronto.ca/services-payments/streets-parking-transportation/road-maintenance/road-sidewalk-repair/.

3.11 Proposed minimum dimensions for an access route. The proposed requirements simplify access requiremets and clarify

the difference between necessary width of a travel lane and the width required for staging. Further research and consultation is required to determine appropriate staging width and length limits. Author's drawing informed by: Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 3-102;103;244 Division B.

3.12 Excerpts from NBCC 2020. Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 3-225;226 Division B.

3.13 Quote from Lawrence Veiller, "NHA Proceedings," 1913. Lawrence Veiller, "National Housing Association Proceedings" (The Academy of Political Sciences, Columbia University, 1913), 211-212.

3.14 The evolution of Fire Zones to contemporary zoning. Although the evolution between the two is not direct, the Fire Zones formed the lineage which would eventually lead to exclusionary zoning. Detached single family housing now dominates urban landscapes in Canada as a result of zoning decisions. Note that multi-unit zoning is not shown on the maps of Calgary, Montreal, and Vancouver. Grey areas refer to all other zones and roadways. Author's drawing informed by: Raphaël Fischler, "Development Controls in Toronto in the Nineteenth Century," Urban History Review / Revue d'histoire Urbaine 36, no. 1 (2007): 16–31, https://doi.org/10.7202/1015817ar.; Yang Sun, "A Visual Guide to Detached House Zones in 5 Canadian Cities," DataLabTO (blog), accessed October 16, 2024, https://www.datalabto.ca/a-visual-guide-to-detached-houses-in-5-canadian-cities/.

3.15 The concept of spatial separation with accompanying tables from NBCC 2020. The type of construction (see Barrier #5) and type of cladding (see Barrier #7) required both have significant impacts on the embodied carbon of a building and rely on large assumptions as outlined in text. Table values highlighted in grey indicate combustible construction permitted; table values highlighted in yellow indicate combustible cladding permitted. Combustible cladding is tightly limited, requiring large setbacks from property lines. Significantly more restrictive limits are in place for unsprinklered buildings. Author's drawing informed by: Canadian Commission on Building and Fire Codes, "National

Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 3-85;87 Division B.

3.16 Comparison of a typical home and the vehicles used to support it over a 60 year life cycle. The data on EV and ICE vehicles presented by Hirz and Nguyen was adapted based on Canadian average electricity emissions. The home in this scenario has an embodied carbon of 375 kgCO2e/m2 and an area of 150 m2, the vehicles are assumed to last 12 years. Neither the building or cars account for maintenance or end of life emissions. Author's drawing informed by: Mario Hirz and Thu Trang Nguyen, "Life-Cycle CO2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems," World Electric Vehicle Journal 13, no. 4 (April 2022): 61, https://doi.org/10.3390/wevj13040061.; Environment and Climate Change Canada, "Where Canada's Greenhouse Gas Emissions Come from: 2024 National Greenhouse Gas Inventory," backgrounders, Government of Canada, May 2, 2024, https://www.canada.ca/en/environment-climate-change/news/2024/05/where-canadas-greenhouse-gas-emissions-come-from-2024-national-greenhouse-gas-inventory.html.

3.17 Comparison of building permits issued in Auckland by areas that were upzoned and not upzoned. Though there are a number of factors which impact the number of building permits issued, Auckland presents a clear case study that upzoning does in fact boost construction. The graph offers a glimpse of what could occur in Canadian cities if given the chance. See source document for further analysis. Figure reproduced from: Ryan Greenaway-McGrevy and Peter C. B. Phillips, "The Impact of Upzoning on Housing Construction in Auckland," Journal of Urban Economics 136 (July 1, 2023): 103555, https://doi.org/10.1016/j.jue.2023.103555.

3.18 Excerpts from interview with Conrad Speckert on June 26, 2024. See Appendix A for full transcript

3.19 Excerpts from NBCC 2020. Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 1-10 Division A, 3-141 Division B.

3.20 Comparison of a typical two-stair building complying with NBCC 2020 and a single-stair building complying with BCBC 2024. See proposed change section for detailed outline of change.

Author's drawing informed by: Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 1-10 Division A, 3-141 Division B.; Ministry of Housing, "British Columbia Building Code" (Province of British Columbia, 2024).

3.21 Summary of historical code requirements for single stair buildings in Canada. Note that the 1927 Uniform Building Code (UBC) did not have any legal bearing in Canada; its inclusion is to show a historical continuity. NC = noncombustible; C = combustible; NP = not permitted; SP = sprinklered. Author's drawing informed by: Keith Calder and Peter Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada" (Sereca Consulting Inc, March 19, 2015).

3.22 Diagram of redundant egress routes throughout time. These solutions are intended to add a layer of safety in an emergency scenario and work in addition to the single internal stair that is required for day-to-day circulation. Note that illustration h) denotes the pressurized core around the single internal stair, not an additional stair. The illustrations are intended to show a range of acceptable solutions but do not encompass all manners enhancing the safety of egress from a building. Author's drawing informed by: Benjamin Oppenheimer, Improvement in Fire-Escapes, United States Patent Office 221855 (Trenton, Tennessee, filed March 26, 1879, and issued November 18, 1879); Lauren Young, "The Creative and Forgotten Fire Escape Designs of the 1800s," Atlas Obscura, December 9, 2016, http://www.atlasobscura.com/articles/the-creative-and-forgotten-fire-escape-designs-of-the-1800s.

3.23 Maximum allowable single stair building heights compared to fire death rate, deaths per fire, and career firefighters per capita. Japan's fire death per capita is relatively normal (1.23 fire deaths per 100,000 inhabitants), while its deaths per 100 fires is exceedingly large (3.77 compared to the next largest 1.31) and, counterintuitively, their number of career firefighters is large (128 firefighters per 100,000 inhabitants, compared to Canada's fairly average 73). There are a number of factors at play which contribute to this discrepancy: arson accounts for approximately 30% of know fire causes during the time period analyzed, while an aging population and more frequent storms have likely counteracted the introduction of fire safety measures. The fire

death per capita has been trending downwards, reaching 1.17 in 2022. Reporting standards may also differ between countries and introduce uncertainty. Author's drawing informed by: Conrad Speckert, "Jurisdictions: Maximum Permitted Height for Single Stair Buildings" (University of McGill School of Architecture, 2022, updated 2024), https://secondegress.ca/Jurisdictions; Nikolai Brushlinsky et al., "World Fire Statistics Report 24," Center of Fire Statistics (International Association of Fire and Rescue Services, 2019), https://www.ctif.org/world-fire-statistics.

3.24 Two stair and single stair project floorplate comparison. While multiple single stair cores can be strung together (La Defense-Nanterre) they generally have smaller floorplates and less bedrooms per storey than two stair buildings Author's drawing informed by: See following figures.

3.25 Floorplate efficiency of two stair buildings in Toronto Author's drawing informed by:

3.26 Floorplate efficiency of single stair buildings across the world Author's drawing informed by:

3.27 Comparative analysis of two stair and single stair buildings with equal floor area. These hypothetical designs have an area of 1500 m2 in order to evaluate the applicability of single stair buildings relative to two stair designs in the Group C, up to 6 Storeys, Sprinklered category. Note that embodied carbon is highly sentative to changes in the number of bedrooms at this scale. Author's drawing.

3.28 Summary of proposed changes to allow single stair buildings. The 6 storey maximum building height corresponds with the maximum height before NBCC high building requirements kick in. Spinklering of balconies, decks, and projections is based on Calder and Senez's 2016 study of "The Key Modes of Fire Spread in Wood-Framed Apartment Buildings" Author's drawing informed by: Conrad Speckert, "The Second Egress: Building a Code Change," accessed September 17, 2023, https://secondegress.ca.; Robert Heikkila, Biswadeep Ghosh, and Kevin Chen, "Single Egress Stair Building Designs: Policy and Technical Options Report," Options and Implications Report (British Columbia: BC Ministry of Housing, June 25, 2024).; Ministry of Housing, "British Columbia Building Code Revision 3" (Province of British Columbia, August 27, 2024).

3.29 Excerpts from NBCC 2020. Canadian Commission on Building

and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 1-3;13 Division A, 3-61;62 Division B.

3.30 Application of building height definition to Group C, up to 6 Storeys, Sprinklered. There are no limits to the number of storeys below grade for Part 9 buildings however they are less likely to be built in practice than in Part 3 buildings which may house parking or other uses. Author’s drawing informed by: Canadian Commission on Building and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 1-3;13 Division A, 3-61;62 Division B.

3.31 Comparison of aerial truck capability with 6 storey building height. Typical aerial capability (red) and new Bronto Skylift (yellow) recently acquired by Toronto Fire Department. Firefighting capability has increased significantly in recent years through taller aerial trucks. Typical aerials range from 22-31 m in reach, allowing for access above 6 storeys. Regardless, most firefighting occurs from within when the building is less than 6 storeys in height. Author’s drawing informed by: Bob Vaccaro, “Toronto’s Bronto Skylift 230-Foot Aerial,” Fire Apparatus Magazine (blog), February 17, 2023, https://www.fireapparatusmagazine.com/magazine/torontos-bronto-skylift-230-foot-aerial/.

3.32 Comparison of the embodied carbon of Marquette Residences as built and under proposed change. Range of total embodied carbon values assumes that remainder of floor area is between 250-500 kgCO2e/m2. Assemblies are assumed based on drawings and photos by architect and typical details. Design b) uses a frost protected slab on grade. Note that the embodied carbon values presented are strictly for material production and do not include site work or excavation. See appendix for full details. Author’s drawing informed by: _naturehumaine, “Marquette Residences,” _naturehumaine, accessed September 9, 2024, https://naturehumaine.com/portfolio/marquette/.; EPDs via One Click LCA, “LCA & EPDs for Construction & Manufacturing,” One Click LCA, https://oneclicklca.com.

3.33 Number of storeys, including basements, compared to building/net floor areas of Group C, up to 6 Storeys, Sprinklered. The black line shows the false assumption of a constant net floor area regardless of the number of storeys. The proposed change would continue the existing relationship between building area and

actual net floor area. Author’s drawing informed by: Canadian Commission on Building and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 3-61;62 Division B.

3.34 Excerpts from NBCC 2020 Canadian Commission on Building and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 1-5;1-10 Division A, 3-60;3-61 Division B.

3.35 Upper limits of Group C residential building height and building area by permitted construction type. “All upper limits depicted must be sprinklered among other requirements that vary by height and area.

3.36 *Noncombustible buildings conforming to the same requirements as 6 storey combustible buildings are permitted to have up to 6000 m2 of building area.” Author’s drawing informed by: Canadian Commission on Building and Fire Codes, “National Building Code of Canada: 2020” (National Research Council of Canada, March 28, 2022), 3-60;3-61 Division B.

3.37 Maximum number of storeys with a load-bearing timber structure in sprinklered residential buildings across the world. Diagram describes the maximum height permitted in prescriptive codes. Timber structure does not distinguish between light wood framing and mass timber. Some storey heights are derived from a maximum height limit. See source document for additional information. Author’s drawing informed by: Birgit Östman et al., “Fire Safety Requirements in Different Regions,” in Fire Safe Use of Wood in Buildings (CRC Press, 2022), 118–48.

3.38 Fire severity outcomes in apartment buildings by construction type and protection system in BC, AB, and MN, Canada, 2005–2015 (NFID Dataset). Confidence intervals can be found in source document. Figure reproduced from: Alex Zheng, Len Garis, and Ian Pike, “Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and Non-Combustible Construction Materials,” Fire Technology 58, no. 4 (July 1, 2022): 1815–25, https://doi.org/10.1007/s10694-022-01223-4.

3.39 Quote from Alex Zheng, Len Garis, and Ian Pike, “Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and Non-Combustible Construction Materials,” 2022. Alex Zheng, Len Garis, and Ian Pike, “Fire Severity

Outcome Comparison of Apartment Buildings Constructed from Combustible and Non-Combustible Construction Materials," Fire Technology 58, no. 4 (July 1, 2022): 1815–25, https://doi.org/10.1007/s10694-022-01223-4.

3.40 Embodied Carbon of structural materials by weight. Note that the concrete value excludes reinforcement which can add a significant amount of embodied carbon. Author's drawing informed by: Galina Churkina et al., "Buildings as a Global Carbon Sink," Nature Sustainability 3, no. 4 (April 2020): 269–76, https://doi.org/10.1038/s41893-019-0462-4.

3.41 Cumulative embodied carbon emissions required for urban construction from 2020-2050 with different adoption scenarios of timber construction. Significant uncertainty levels exist in the data as a result of unknown floor area per capita and some variability in material emissions. Author's drawing informed by: Galina Churkina et al., "Buildings as a Global Carbon Sink," Nature Sustainability 3, no. 4 (April 2020): 269–76, https://doi.org/10.1038/s41893-019-0462-4.

3.42 Embodied carbon of structural systems by material, divided into LCA phases. Extraction, manufacturing, and construction (A1-A5), maintenance and replacement (B1-B5), and end of life (C+D). Author's drawing informed by: Austin Himes and Gwen Busby, "Wood Buildings as a Climate Solution," Developments in the Built Environment 4 (November 1, 2020): 100030, https://doi.org/10.1016/j.dibe.2020.100030.; Roberto Minunno et al., "Investigating the Embodied Energy and Carbon of Buildings: A Systematic Literature Review and Meta-Analysis of Life Cycle Assessments," Renewable and Sustainable Energy Reviews 143 (June 1, 2021): 110935, https://doi.org/10.1016/j.rser.2021.110935.

3.43 Excerpts from interview with Beth Weckman on September 5, 2024. See Appendix A for full transcript

3.44 Excerpts from NBCC 2020 Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 1-6 Division A, 3-17;3-19 Division B.

3.45 Acceptable combinations of maximum exposed mass timber elements in the NBCC and IBC for residential uses. All scenarios (including the IBC) must be sprinklered. The IBC combination refers to Type IV-C construction which is limited to 8 storeys compared to the 12 storeys permitted in the NBCC examples.

The FSR of the timber used in mass timber elements ranges between 35 and 70. Author's drawing informed by: "Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 3-17;3-19 Division B.

3.46 "2024 International Building Code" (International Code Council, Inc., August 2023), https://codes.iccsafe.org/content/IBC2024P1, section 602.4.3."

3.47 Phases of a mass timber compartment fire and accompanying char process illustrating potential varied nature as result of decay, smouldering, and char fall-off. Author's drawing informed by: Harry Mitchell et al., "Review of Fire Experiments in Mass Timber Compartments: Current Understanding, Limitations, and Research Gaps," Fire and Materials 47, no. 4 (2023): 415–32, https://doi.org/10.1002/fam.3121.

3.48 Loss of section in mass timber elements as a result of charring. Author's drawing informed by: Alar Just et al., "Load-Bearing Timber Structures," 2022, 227–76, https://doi.org/10.1201/9781003190318-7.

3.49 Overview of current research comparing compartment area and exposed surface area. Further research is needed in large scale compartments as might be found in office spaces or family-sized residential units. Refer to source for further information relating the compartment test to research paper. Author's drawing informed by: Harry Mitchell et al., "Review of Fire Experiments in Mass Timber Compartments: Current Understanding, Limitations, and Research Gaps," Fire and Materials 47, no. 4 (2023): 415–32, https://doi.org/10.1002/fam.3121.

3.50 Typical EMTC and noncombustible alternative multi -unit residential floor assemblies. The assemblies are all designed to support residential loading (1.9 kPa) and a 50 mm concrete topping (1.5 kPa) at a 6.0 m span. Additionally, they all have a 120 min. FRR regardless of encapsulation. Author's drawing informed by: "Cross-Laminated Timber (CLT) Product Specifications and Span Tables" (Element5, February 2022).

3.51 Embodied carbon of typical EMTC and noncombustible alternative mulit-unit residential floor assemblies. The embodied carbon of the assemblies does not account for any membranes, fasteners, connections, other auxiliary products, or floor finishes. Author's drawing informed by: EPDs via One Click LCA, "LCA

& EPDs for Construction & Manufacturing," One Click LCA, https://oneclicklca.com.

3.52 Proposed acceptable combinations of maximum exposed mass timber elements. Author's drawing.

3.53 Excerpts from NBCC 2020 Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 1-5;1-10 Division A, 3-7 Division B.

3.54 NBCC 2020 material combustibility classification. Combustible components are allowed in limited quantities in noncombustible construction. Heavy timber and encapsulated mass timber construction use combustible material in dimensions large enough to mitigate some degree of fire risk. Author's drawing informed by: Amirouche Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials: A Case Study of Canada," Fire and Materials 48, no. 7 (July 3, 2024): 737–51, https://doi.org/10.1002/fam.3227.

3.55 Vertical tube furnace diagram used in CAN/ULC-S114 to determine Noncombustibility Author's drawing informed by: Amirouche Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials: A Case Study of Canada," Fire and Materials 48, no. 7 (July 3, 2024): 737–51, https://doi.org/10.1002/fam.3227.

3.56 High level overview of the testing standards and construction types throughout the development of the NBCC Author's drawing informed by: Amirouche Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials: A Case Study of Canada," Fire and Materials 48, no. 7 (July 3, 2024): 737–51, https://doi.org/10.1002/fam.3227.

3.57 Risk of death and injury according to construction type and building size. Author's drawing informed by: Xia Zhang, Jim Mehaffey, and George Hadjisophocleous, "Case Studies of Risk-to-Life Due to Fire in Mid- and High-Rise, Combustible and Non-combustible Buildings Using CUrisk," March 27, 2015.

3.58 Comparison between flame spread rating and peak heat release rate of common materials, coded by combustibility. Author's drawing informed by: Amirouche Sadaoui, Christian Dagenais, and Pierre Blanchet, "A Comparative Study of Fire Code Classifications of Building Materials," Fire 7, no. 7 (July 2024): 252, https://doi.org/10.3390/fire7070252.

3.59 Analysis of Knudrisraekkern (Denmark) through the NBCC. This building exceeds the allowable limit for combustible cladding. It is uncertain if it is sprinklered, which is a requirement for Group C, up to 12 Storeys, Sprinklered category. Author's drawing.

3.60 Analysis of Lisbjerg Bakke (Denmark) through the NBCC. Although this building is largely compliant, which gives hope to low carbon design in Canada, its internal finish may exceed the FSR limit in the NBCC. Further, its form and density, though permitted, is rarely built in Canada as a result of lot size, financialization, and zoning bylaws. Author's drawing.

3.61 Embodied carbon of common insulations and cladding materials. Author's drawing informed by: Chris Magwood, Erik Bowden, and Melanie Trottier, "Emissions of Materials Benchmark Assessment for Residential Construction" (Passive Buildings Canada and Builders for Climate Action, 2022).; Geoffrey Turnbull et al., "Embodied Carbon Values in Common Insulation Materials" (KPMB Architects, KPMB LAB, May 2021).

3.62 Waterfall graph of reductions identified by this thesis that are concerned with noncombustibility. Author's drawing.

Introduction

Objective

The primary goal of this research is to identify overly stringent fire safety regulations in the National Building Code of Canada (NBCC) which inhibit the ability to construct low embodied carbon housing. Though identifying the barriers (and even implementing the proposed solutions) will not reduce the embodied carbon of future residential buildings, removing these barriers allows for this possibility to take place where the current regulatory scheme does not. The barriers identified by this thesis are by no means the only Code regulations, or even fire safety regulations, that restrict low embodied carbon housing. Instead, they were selected to illustrate the pervasive manner in which the NBCC mandates embodied carbon. They also represent the part of the Code that is most relevant to architects which has a critical role in determining downstream embodied carbon impacts.

In concert with the primary objective, the research aims to develop a greater understanding of the importance of embodied carbon in relation to housing. Particularly through analyzing the role that scale plays in carbon efficient housing in order to empower low carbon design decisions in missing middle and mid-rise housing. Further, the research seeks to illustrate the NBCC as a historical document rather than a strictly technical one. The goal is that a broader perspective will enable architects and practitioners to better appreciate the malleability of the code and encourage their technical and political involvement in shaping future editions. Additionally, the research aims to break down some of the assumptions that underpin the NBCC with the intention of examining the legitimacy of current regulations. Finally, the work establishes a depth of information that correlates fire safety and embodied carbon to quantify which regulations are the most pressing to review in order to reduce emissions.

While the objective of identifying the barriers is to catalyze action, either through direct code change proposals or advocacy for broader building code shifts (e.g., performance targets), it also serves the critical role of establishing starting points for future research in this field. The barriers identified will be analyzed for their impact on fire safety and embodied carbon. Drawing from this research, proposed changes to the Acceptable Solutions in the NBCC will be suggested

to enable the reduction of carbon while also providing equal or better fire safety that meets the acceptable level of risk assumed by the Code. The current NBCC regulations take a number of considerations into account, as outlined by the objectives stated in Division A, Part 2; in light of the importance of embodied carbon and its relationship to the ongoing climate and housing crises, a holistic review of the NBCC is warranted to account for the embodied carbon implied by existing requirements.

Scope

This thesis will identify, analyze, and propose solutions to regulatory barriers within the NBCC and related Canadian regulatory bodies, to low embodied carbon missing middle and mid-rise housing typologies. The work is divided into three main parts. The first discusses the emissions associated with the production, maintenance, replacement, and eventual disposal of residential construction materials. Relying on existing research, this section will touch upon the importance, methods of measuring, relationship to housing, and the limits of current regulations as they relate to embodied carbon. The second will document the development of the NBCC and its associated assumptions, drawing on existing research with additional analysis and commentary. Attention will also be paid to the ways in which fire safety has changed during this time period, including advancements to materials, construction methodologies, firefighting, fire detection, and fire suppression. The third part, which constitutes the bulk of the novel research presented by this thesis, identifies, analyzes, and proposes changes to the barriers to low embodied carbon housing. Barriers will be grouped by their scale of impact, including a brief commentary on the systemic meta-barriers to the application of regulations. Each barrier will be broken down to analyze its regulatory interpretation, followed by its fire safety impact, embodied carbon impact, and the proposed change.

Part One examines the embodied emissions associated with the construction, upkeep, and eventual demolition (or deconstruction) of housing. The context of Canadian and global carbon emissions is explored through the frameworks of limiting climate change to +2°C, the global carbon cycle, and the relationship to a Canadian housing shortage. Limiting further greenhouse gas emissions (GHG) is essential in order to mitigate the ongoing climate crisis.[1] Despite this, the world will need 40 billion m^2 of additional residential space by 2050.[2] Within Canada, the 3.5 million homes needed to close the current shortage[3] represents the most pressing need for new construction and must be met with low embodied carbon (the emissions associated with the production, maintenance, and disposal of materials) and low operational carbon (the emissions associated with the heating, cooling, and lighting of buildings) construction in order to limit its contribution to global warming. Further, as operational carbon decreases through the decarbonization of

1. "Climate Change 2023 Synthesis Report."
2. Marinova et al., "Global Construction Materials Database and Stock Analysis of Residential Buildings between 1970–2050."
3. CMHC, "Canada's Housing Supply Shortage."

Canadian electrical grids, the importance of addressing embodied carbon increases. The parameters of measuring embodied carbon in buildings are explained; the boundaries for different phases of a life cycle analysis (LCA) are reviewed, including the differences between operational, embodied, and biogenic carbon. Common material life cycles and emissions are reviewed, followed by an analysis of how they come to form housing. Missing middle and mid-rise housing presents the opportunity for the lowest embodied carbon form of housing although its construction is tightly controlled by the NBCC, which makes it an ideal candidate for removing the barrier to embodied carbon reduction.[4] Despite representing roughly half of the whole life carbon of a building,[5] embodied carbon is not addressed by the Code, whereas operational carbon is.[6] [7] The role and effect of carbon emission regulation is analyzed with a focus on the state of embodied carbon regulation within Canada and globally. Existing municipal regulations, federal mandates, and proposed limits are examined.

Part Two evaluates the regulatory frameworks which determine the embodied carbon of housing in Canada. While there are a multitude of nested, accessory, and competing regulatory bodies which range from planning guidelines, design standards, testing standards, and industry regulation, this work will focus on the primary governing document for architecture in Canada: the NBCC. Within the Code, Part 3 (which is responsible for fire protection, occupant safety, and accessibility) is the most relevant to architects and broadly presents the framework for design decision-making which has explicit carbon impacts through form, density, and materials selection. Further, decisions made by the architect pursuant to Part 3 of the NBCC largely drive the subsequent application of the other parts of the Code (e.g. Part 4 structural) which have their own associated embodied carbon emission reduction potentials. Each regulation in the Code is tied to a number of objectives, functional statements, and intent statements, which explain the goal (or goals) it seeks to achieve and the manner in which it does so.[8] As our planet warms, it becomes increasingly important that embodied carbon is considered in these requirements across the board, particularly in Part 3 of the NBCC given its outsized impact on building design. The development of the Code will be studied in order to understand how existing regulations came into being. Examining the NBCC as a historical and political document, in addition to its role as a technical baseline, enables the core tenets to be deconstructed and considered as individual pieces which contribute to the whole. The acceptable risk that the Code is assumed to create will be examined

4. Rankin et al., "Embodied GHG of Missing Middle."
5. CAGBC, "Embodied Carbon: A Primer for Buildings in Canada."
6. Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 2-5;6 Division A.
7. Canadian Commission on Building and Fire Codes, "National Energy Code of Canada for Buildings: 2020."
8. Canadian Commission on Building and Fire Codes, "NBCC 2020," viii, 2-2;3-3 Division A."

and contrasted with performance-oriented codes. Finally, the contemporary fire safety landscape will be explored, focussing on the impact of sprinklering, inclusion of smoke detectors, integration of fire statistics, and firefighting tactics.

Part Three identifies barriers to low embodied carbon housing within Part 3 of the NBCC. Barriers were chosen based on their relationship to fire safety and embodied carbon, falling within the professional responsibility of the architect, and presenting the best opportunity to effect change. Using this selection framework, seven barriers were identified and characterized into three scales of impact: urban, building, and material. These three scales of impact were chosen because they form the basis of an architect's decision-making processes and illustrate the multifaceted impact that regulation has on the embodied carbon of a project. The urban scale presents the project frameworks (where will the building be located), the building scale establishes the schematic design (how large will the building be), and finally, the material scale develops the project and begins specifying assemblies (what materials will be used). Similarly to any design framework, the initial decisions have an outsized impact on the outcome of a project. While they may not directly inform all future decisions, they tend to form the parameters that the next level of decisions must confine to.

In conjunction with the background research, potential barriers were identified through expert interviews (see Appendix A) which aimed to highlight the anecdotal and experiential impact of the black-and-white lines of Code. Interviewees were selected based on the author's familiarity with their work and its application to the subject matter being researched by this thesis. The conversations attempt to explain some of the human and practical challenges that come up when the NBCC is applied in practice, and reveal some of the externalities that appear when life safety regulations conflict with other desires or requirements (economic challenge of building more housing, environmental challenge of reducing carbon). In addition, they serve as a counterpoint to some of the experiential arguments that are presented in favour of more onerous, more restrictive, or status quo actions. The perspectives privileged by these interviews are not intended to undermine other considerations (e.g. the fire service), but rather to broaden the conversation to understand the impacts of fire safety beyond its intended scope in order to examine other ways in which we might work.

After identifying barriers, this thesis aims to quantify their fire safety and embodied carbon impacts through a mix of literature and novel

research. Studies on fire dynamics are used to approximate the assumed risk that the regulations attempt to mitigate and examples of innovative or alternative fire safety strategies are highlighted. Research on the embodied carbon implicit in the regulations is difficult to find given the newfound importance of these emissions and the variability of applying the rules. Quantifying this impact often relies often on conducting a life cycle assessment (LCA) to assess the scale of associated emissions. Based on the analyzed research, a solution to each barrier is proposed, which range from specific rewritten lines of Code to outlining areas of further research needed.

The barriers identified in this thesis are not an exhaustive list of regulations which impact carbon. Instead, this work provides a necessary, focused examination of the parts of the NBCC that are most relevant to the architect. This work centers on the confluence of fire safety and embodied carbon research – a critical intersection rarely investigated. As Canada works towards low carbon architecture to achieve net-zero emissions (however that may be defined), it is of increasing importance to evaluate whether the frameworks within which we work serve our needs appropriately. There is no research which investigates the role of fire safety on embodied carbon, though there is a growing body of research which investigates the role of regulation in general on embodied carbon.[9] [10] The final chapter provides summarized findings, significance of the work, and recommendations for future research.

As a whole, the thesis does not present the barriers as absolute hinderances, nor are the solutions intended to be cure-alls. The breadth of barriers is intended to present a number of avenues for future research and consideration. Building fire safety, despite being heavily regulated, is severely under-researched (and understandably so, given the enormity of variables, cost, and time to conduct this research). The seven barriers identified provide starting points for more thorough research into their validity in Canadian regulation, and taken together, provide an understanding of the depth of indirect impact that these regulations can have on the embodied carbon of a city, building, or wall assembly.

9. Ha/f Climate Design, "Urban Design Guidelines Embodied Carbon Study."
10. Arceo, MacLean, and Saxe, "Material Intensity in Single-Family Dwellings."

Methodology and Limitations

This thesis begins with a literature review of the importance of embodied carbon in the built environment in the face of a simultaneous housing crisis and climate catastrophe. Particular focus is on "grey literature", the policy documents, reports, and white papers that are emerging in this relatively new area of research. Existing research is analyzed for its overall impact on embodied carbon reduction and categorized by the scale. Given the breadth of strategies that can reduce embodied carbon, from tax incentives to zoning to construction practices, this thesis does not evaluate all of the potential actions but instead looks at those that pertain to building code and combustibility. This section points towards sections in the Code that might warrant additional consideration to ensure that the regulations enable low embodied carbon construction without compromising fire safety.

Following this, the thesis analyzes the NBCC as a historical document that was created simultaneously to, but not always in concert with, other advances in building fire safety. Analysis of current and historical versions of the NBCC (and its predecessors) establish its historical roots and subsequent development to the regulatory document Canada uses today. Understanding the NBCC as a historical artifact of relatively arbitrary decisions, rather than a purely scientific body of regulation, highlights the underlying limitations of such a document and the need to evaluate its approach to fire safety. Examples of regulations that have not advanced significantly since their inception are presented and analyzed. In order to assess the current state of fire safety in the NBCC, the goals, definitions, and underlying assumptions are described. Then, to better understand the opportunities and limitations of the current iteration, the development of fire detection and suppression techniques, the limitations to testing, and the relative risk of combustibility are outlined.

Once the general shortcomings of the Code are understood and the importance of embodied carbon is highlighted, the thesis outlines seven regulatory barriers identified through a combination of the aforementioned literature reviews and interviews with subject experts. These barriers are categorized by their scale of their influence to urban design, building form, and material assemblies. The NBCC regulations are analyzed for their role in fire safety relying on

contemporary literature and international approaches to attempt to quantify these (previously unknown or undescribed) impacts. The relative impact of the barriers on embodied carbon is measured primarily through comparative analysis using LCA software and supported by literature. Informed by these findings, detailed Code changes are proposed which address the barriers to low embodied carbon construction and the regulatory environment of Canada. Finally, a description of the future research that would be required to support the proposed Code changes under regulatory and public scrutiny is provided.

There are two limitations to this novel research; the first is that, while the proposed solutions may identify the underlying risk assumptions of a portion of the Code, some cannot accurately quantify the historical risk which the regulation aimed to address (at the time of its introduction) as a result of minimal historical documentation. Thus, it is difficult to determine whether the proposed change appropriately addresses the original risk, ultimately perpetuating the cycle of changes aimed to address relatively unquantified risk. Where this is the case, the proposed solutions are derived from logical arguments made within the bounds of existing regulation rather than in a performance-based manner. Secondly, given that the research focussing on the embodied carbon impact of regulations is novel, it is impossible to say whether the barriers discussed are the most impactful ones. Quantifying the carbon impact of potential changes is both difficult and has not been previously studied which limits the ability to estimate a barriers implicit embodied carbon prior to selection.

Overall, this thesis provides unprecedented support for the addition of embodied carbon as a crucial consideration to the NBCC. Current Canadian regulation aims to ensure that buildings achieve an acceptable level of risk while meeting the objectives of occupant safety (OS), health (OH), accessibility (OA), building protection (OP), and environmental protection (OE). Although the goal of the OE objective is "to limit the probability that, as a result of the design or construction of the *building*, resources will be used in a manner that will have an unacceptable effect on the environment,"[11] the "unacceptable effect on the environment" is only measured by OE1.1 - excessive use of energy. This thesis challenges the Code's current definition of "excessive use of energy" to pertain beyond operational carbon and include embodied carbon. The incorporation of embodied carbon considerations could also fall within OS and OH, due to the increased mortality under global warming conditions.

11. Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 2-5;6 Division A.

In summary, this thesis reviews the concept of embodied carbon and critically considers its implications in the ongoing climate and housing crises. It examines the NBCC and how its method of development has shaped the current regulations with an eye towards its role as a political document to enact change. Finally, the thesis provides an investigation into the ways in which the Code enables or disenfranchises design requirements with an impact on embodied carbon and offers proposed changes that allow for the potential of reduced embodied carbon without diminishing fire safety.

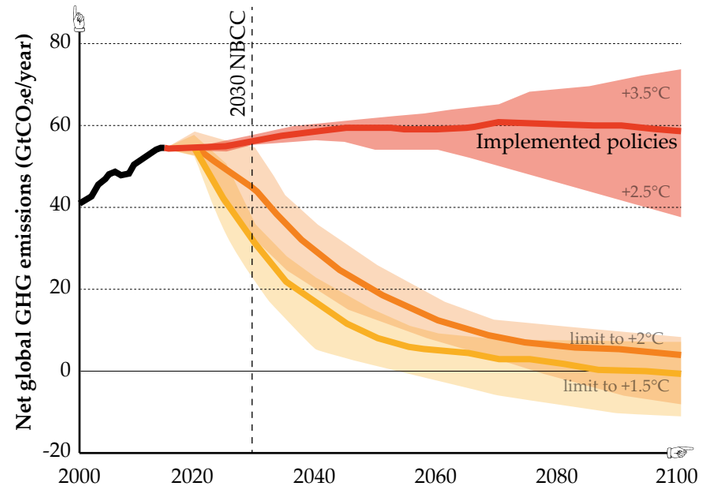
Part One:
Embodied Carbon and our Burning House

What's the Big Deal?

Climate change presents an existential threat to humanity.[12] To avoid catastrophe and to keep global temperatures from rising above +2°C as put forward by the International Panel on Climate Change (IPCC), significant emission reductions are needed across all sectors (though it may already be too late)[13] (figure 1.01).[14] Far from abstract, the mortality cost of carbon emissions has been quantified: 4,434 tCO_2e emitted cause one excess death globally, the approximate equivalent of one 6-storey apartment building.[15] The architecture and construction industry are complicit in these emissions; the built environment is responsible for approximately 39% of global greenhouse gas (GHG) emissions.[16] The GHG emissions associated with material extraction, manufacturing, and use (largely in buildings), contributes between 11%-25% of total GHG emissions (figure 1.02).[17] [18] These emissions are referred to as embodied carbon. Until relatively recently, attention has been focussed on reducing the emissions related to the heating and cooling of buildings (known as operational carbon), yet as we transition to cleaner energy globally, the proportion of embodied carbon increases.[19]

This trend is exceedingly true in Canada; as provinces move towards renewable energy, heating, cooling, and lighting emissions have fallen to be on par with the material emissions required to construct new buildings, when compared over the lifespan of a building.[20] Embodied carbon makes up between 8%-13% of Canadian emissions,[21] [22] which, while lower than other national averages, makes up a significantly larger per capita value (2.3 tCO_2e) than the USA (1.2 tCO_2e), China (1.9 tCO_2e), and Norway (1.1 tCO_2e), as a result of large transportation, oil, and gas emissions (figure 1.03).[23] [24] Despite the federal government's goal of 40%-45% reduction of GHG emissions by 2030 and net-zero by 2050,[25] the role of embodied carbon reductions is largely absent from Canada's 2030 Emissions Reduction Plan.[26] The importance of this omission is highlighted by the time value of embodied carbon emissions; all of the embodied emissions are released before the building if occupied. In a high performance building in Canada that finished construction in 2025, as much as 99% of the cumulative emissions of a will be the result of embodied carbon by 2030 (figure 1.04).[27] This is to say nothing of the

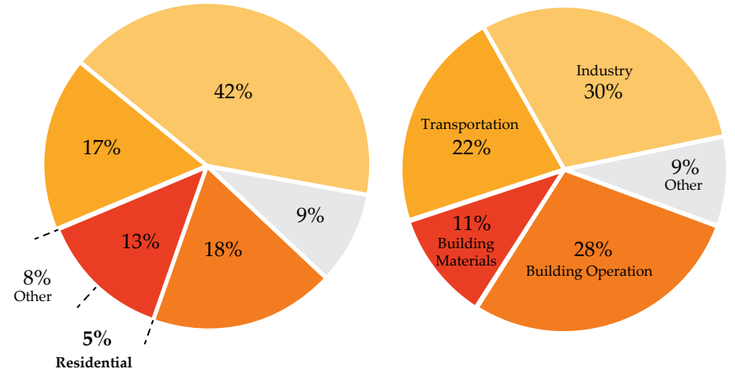
12. "Climate Change 2023 Synthesis Report."
13. Leake, "It's Too Late to Save Britain from Overheating, Says UN Climate Chief."
14. "Climate Change 2023 Synthesis Report."
15. Bressler, "The Mortality Cost of Carbon."
16. International Energy Agency, "2019 Global Status Report for Buildings and Construction."
17. Huang et al., "Carbon Emission of Global Construction Sector."
18. Hertwich et al., "Resource Efficiency and Climate Change."
19. Pauliuk et al., "Global Scenarios of Resource and Emission Savings from Material Efficiency in Residential Buildings and Cars."
20. CAGBC, "Embodied Carbon: A Primer for Buildings in Canada."
21. Yoffe et al., "Mapping Construction Sector Greenhouse Gas Emissions."
22. Huang et al., "Carbon Emission of Global Construction Sector."
23. Canada, "Where Canada's Greenhouse Gas Emissions Come from."
24. Wambersie and Ouellet-Plamondon, "Developing a Comprehensive Account of Embodied Emissions within the Canadian Construction Sector."
25. Minister of Justice, Government of Canada, Canadian Net-Zero Emissions Accountability Act.
26. Environment and Climate Change Canada, "2030 Emissions Reduction Plan: Canada's Next Steps for Clean Air and a Strong Economy."
27. CAGBC, "Embodied Carbon: A Primer for Buildings in Canada."



f 1.01

Cumulative GHG emissions and global warming outcomes. Implemented policies result in emissions which lead to a warming of 2.2-3.5 deg. C.

Author's drawing reproduced from: "Climate Change 2023 Synthesis Report" (Geneva, Switzerland: IPCC, 2023), doi: 10.59327/IPCC/AR6-9789291691647.



f 1.02

Canadian and global GHG emissions by sector.

Approximately 39% of building material emissions are the result of residential construction in Canada, followed by 20% from non-residential buildings, 17% from oil and gas construction, and 14% from infrastructure.

f 1.03

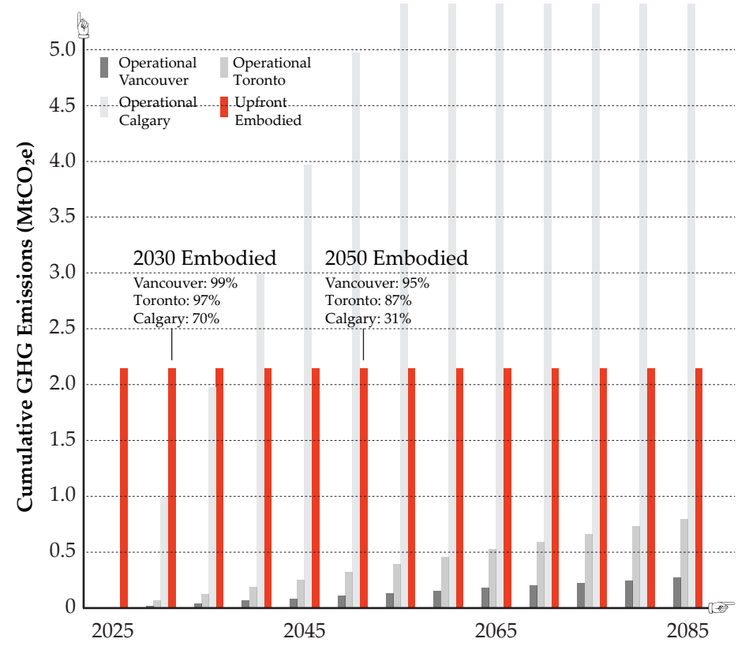
Per capita embodied carbon emissions from the construction sector by country.

Although only 13% of Canada's emissions are from the construction sector, the total emissions are 87 MtCO2e.

other impacts that material extraction, product manufacturing, and end of life practices cause to biochemical flows, ecosystem integrity, and freshwater change, which, although they are beyond the scope of this thesis, contribute to exceeding our planetary boundaries.[28]

These needs, of fatal significance to our home planet, are in tension against another crisis which also affects our home, albeit on a different scale. Globally, our population is set to grow by 18% through 2050 to a population of 9.7 billion.[29] Though the world population is only set to grow by 1.5 billion, urban populations will grow by 2.4 billion,[30] which will require an additional 40 billion m2 of living space.[31] Assuming Canada's population grows at the same rate as the world, this would mean an additional 195 million m^2 of housing - nearly a third of the land area of the City of Toronto (or half of Montreal or twice Vancouver) (figure 1.05).[32] Worryingly, single-family homes are the most common housing type in Canada and also the most carbon intensive.[33] The current housing stock is nearly 53% single-family houses with all low-rise typologies accounting for 71% of dwellings, [34] which makes residential buildings account for approximately 40% Canadian embodied carbon (figure 1.02).[35] These low-density land use decisions have further impact than just their embodied carbon; the Canadian Mortgage and Housing Corporation (CMHC) estimates that Canada will need another 3.5 million homes by 2030 to close its current housing shortage.[36] Current emissions associated with new construction combined with future housing needs does not bode well, potentially putting climate catastrophe avoidance out of reach; Canada is on track to emit 400% more carbon than its climate targets allow in order to close the current housing shortage.[37] The growing demand for housing and the need to reduce carbon emissions requires that Canada takes drastic steps to immediately and substantially reduce the embodied carbon of residential buildings.

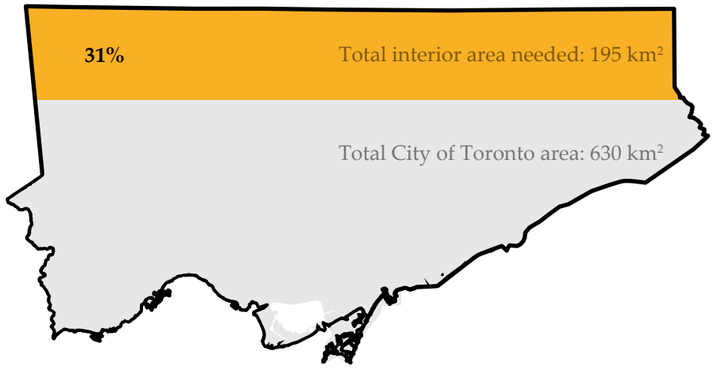
28. Richardson et al., "Earth beyond Six of Nine Planetary Boundaries."
29. United Nations Department of Economic and Social Affairs, Population Division, "World Population Prospects 2024."
30. Swilling et al., "The Weight of Cities: Resource Requirements of Future Urbanization."
31. Marinova et al., "Global Construction Materials Database and Stock Analysis of Residential Buildings between 1970-2050."
32. Government of Canada, "Census Profile, 2016 Census - Toronto, Ontario."
33. Rankin et al., "Embodied GHG of Missing Middle."
34. Government of Canada, "2021 Census of Population."
35. Yoffe et al., "Mapping Construction Sector Greenhouse Gas Emissions."
36. CMHC, "Canada's Housing Supply Shortage."
37. Rankin and Saxe, "A Future Infrastructure Growth Model for Building More Housing with Less Embodied Greenhouse Gas."



f 1.04

Cumulative emissions from a high performance building comparing embodied carbon and operational carbon based on city location.

Provinces with low carbon electricity grids like British Columbia, Ontario, Quebec, and Newfoundland and Labrador show that emissions are dominated by embodied carbon. In high carbon electricity provinces like Nova Scotia and Alberta, even though over the whole life operational carbon exceeds embodied carbon significantly under current scenarios, decarbonization is coming.



Total Interior Living Space Needed in Canada by 2050

f 1.05

Total interior living space required to house Canada's growing population through 2050 compared to the area of the City of Toronto.

Research suggests that although Canada will not grow at the same rate as the global average though 2050, it will exceed the global average by 2060 which suggests Canada will need significant new construction long into the future.

Measuring Embodied Carbon

LCAs and EPDs

The whole life carbon of a building, that is, the total amount of carbon dioxide equivalent (typically measured in $kgCO_2e$) emitted to the atmosphere throughout the duration of the building's life, can be divided into two distinct parts: embodied carbon and operational carbon. Operational carbon accounts for the energy used to heat (including hot water), cool, and light the building during its operation. This type of carbon has been the focus of most sustainability work up to this point in time, largely due to the ease of measurement and end-user cost.[38] In fact, leading building scientist, Dr. John Straube noted in 2010 that "scientific life-cycle energy analyses have repeatedly found that the energy used in the operation and maintenance of buildings dwarf the so-called "embodied" energy of the materials."[39] Given the evidence available in 2010, this certainly seemed to be the case. However, as supply chain and product reporting increased in availability and depth, the true carbon cost of materials has been brought to light. Embodied carbon refers to all of the carbon associated with the production and maintenance of buildings. Typically thought of as the emissions from the extraction, transportation, and manufacturing of products (known as "upfront carbon", phases A1-A3 make up the bulk of emissions), it also encompasses the construction emissions, repair, replacement, and end-of-life processes associated with a building's use.

A life cycle assessment (LCA) is a widely used methodology for measuring the environmental impacts of buildings, and the materials that compose them. The assessment is made up of four stages: manufacturing (A), in-use (B), end of life (C), and beyond building life cycle (D) (figure 1.06). There are a multitude of independent, national, and international standards which may be used to measure the carbon impact of a building, and while they vary slightly from one another, typically they take a cradle-to-grave approach, measuring the impact from extraction through to disposal (which excludes the notoriously difficult to measure D stage).[40] LCAs rely on information contained within environmental product

38. Ahmed Ali, Ahmad, and Yusup, "Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector."
39. John Straube, "BSD-001: Why Energy Matters."
40. Khan et al., "Life Cycle Assessment of Embodied Carbon in Buildings."

declarations (EPDs) to determine the emissions associated with each material. EPDs are standardized documents that manufacturers or independent third parties produce which provide information on the environmental impacts of a specific product or a range of products (e.g. a Province-wide concrete average). Typically, these documents report on the embodied carbon intensity of a project, the amount of CO_2 equivalent emissions associated with the production of 1 m^2 of floor area ($kgCO_2e/m^2$). Canada uses a combination of building assessment documents; the European standard EN 15978 is used for LCA methodology, while ISO 21930 (more common in North America) is used for EPDs.[41]

Both LCAs and EPDs are becoming much more common, as clients are increasingly interested in reducing emissions and architecture firms seek the same goal under their own volition,[42] although the percolation of the importance of this issue through to the general population of architects in Canada is still just starting.[43] Current efforts to quantify and reduce embodied carbon have primarily focussed on structural and enclosure assemblies – given their relative simplicity, scope of architects, and significance to the total portion of carbon. Quantifying the impact of materials is only possible through the data transparency provided by manufacturers and is reported through a number of environmental indicators; this thesis focusses solely on the global warming potential (GWP), measured in $kgCO_2e$. EPDs and LCAs allow for the identification of areas of high emissions, the comparison of similar materials, and the evaluation of potential substitutions. In this thesis, whole-building LCAs are not performed, given the specificity with which they apply to the individual conditions being evaluated. Instead, partial LCAs are completed in concert with average emission intensities to approximate the impact of a given code requirement.

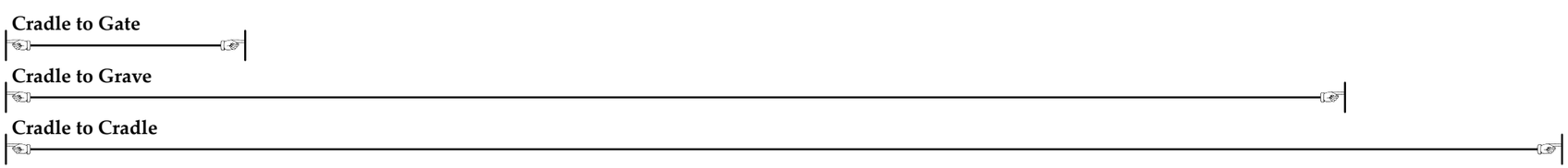
Common Materials

Timber

Wood has traditionally been the building material of choice in North America. Abundant forests and ease of workmanship make this material incredibly versatile and cheap. In Canada, low-rise construction of dimensional lumber has proliferated and recent regulatory change has allowed for this material to be used for up to 6 storeys.[44] Though heavy timber (solid structural members sawn from a single tree) has been prevalent as long as we have been able

41. Bowick et al., "National Guidelines for Whole-Building Life Cycle Assessment."
42. Zizzo and Doran, "Regulating Embodied Emissions of Buildings: Insights for Ontario's Municipal Governments."
43. Royal Architectural Institute of Canada, "Whole Building Life Cycle Assessment Workshops."
44. Canadian Commission on Building and Fire Codes, "National Building Code of Canada: 2020" (National Research Council of Canada, March 28, 2022), 3-61;62 Division B.





f 1.06

Life cycle assessment stages and component phases.

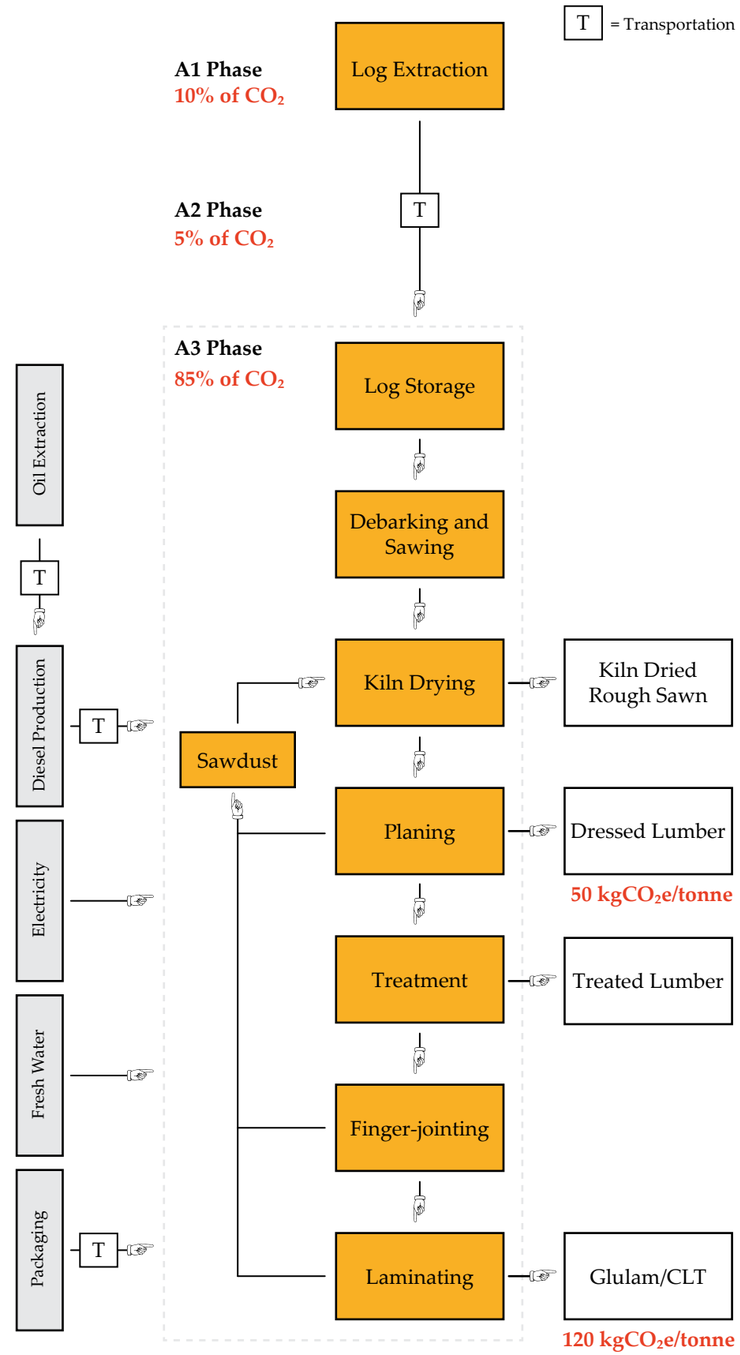
Phases B8 and B9 are often only included in infrastructure projects and aim to account for the carbon emitted through the utilization of a roadway by cars for example. These phases offer a theoretical appraoch to quantifying the lifestyle that a building supports.

to cut down trees, its adoption as a building material has been hindered by availability and cost. Mass timber enables the use of smaller members to create a solid member of larger dimension and has recently been regulated for buildings up to 12 storeys.[45] Timber, as with any biogenic material, has the benefits of being a renewable resource, relatively low energy to manufacture, and sequesters carbon into the material as it grows (figure 1.07).

Recently, as the importance of embodied carbon has come into focus, greater attention has been paid to timber buildings as a result of the ability for trees to absorb and sequester atmospheric CO2 through photosynthesis as they grow. Once they are cut and sawn into timber, they continue to hold this carbon for as long as they are in use. [46] The carbon stored by wood (and other bio-based materials) is referred to as biogenic carbon. Biogenic carbon is released back into the carbon cycle either through decomposition (largely into soil carbon) or incineration (largely atmospheric carbon), at the end of its life. Integrating this storage mechanism into an LCA is typically done through one of two methods; -1/+1 or 0/0. Though they should provide the same results if applied correctly, the first approach subtracts biogenic carbon in the 'A' stage and adds it to the 'C' stage, whereas the second ignores the biogenic carbon under the assumption that the amount of CO2 sequestered equates to the amount of CO2 released at end of life.[47] The -1/+1 method has the benefit of being able to give different weights to emissions by the year they occur, although it can be misleading if the full life cycle isn't accounted for. This thesis uses the 0/0 method to simplify assumptions and ensure that the impacts of bio-based materials are not understated, after all, forests sequester carbon, buildings do not.

Critically, the fundamental assumption that wood is carbon neutral is only correct if the timber is harvested through sustainable forestry.[48] The measurement of sustainable forestry is contentious; most approaches characterize the biogenic carbon increase from forest growth or regrowth as offsetting to the carbon emissions from harvesting. This approach is not entirely accurate, since the forest growth happens (in nearly all scenarios) whether logging occurs or not. Estimates suggest that global emissions for wood harvests will be between 3.5-4.2 $GtCO_2e$/year from 2010-2050. [49] These emissions may be conservative as they do not account for changes in soil carbon, although they still represent savings of 0.8-0.9 $GtCO_2e$/year relative to substitutions of steel, concrete, or propane. The findings suggest that simply replacing all future construction material with wood is not enough to reduce emissions, systemic shifts must occur

45. Canadian Commission on Building and Fire Codes, 3-60 Division B.
46. Jensen and Craig, "Wood in Construction - 25 Cases of Nordic Good Practice."
47. Andersen et al., "Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods."
48. Andersen et al.
49. Peng et al., "The Carbon Costs of Global Wood Harvests."



f 1.07
Embodied carbon flowchart for timber products.

as well; if future forest harvests are reduced, forest growth can act as a carbon sink rather than just an offset.

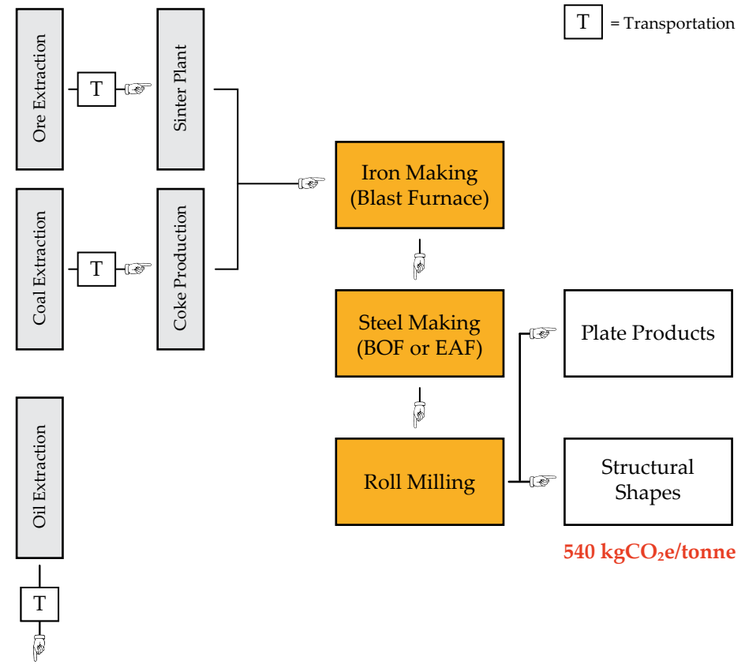
Steel

Typically manufactured by using a basic oxygen furnace, which relies on fossil fuels, steel production in Canada is generally headed towards electric arc furnaces and other low carbon processes (figure 1.08).[50] These tend to take advantage of the relatively clean Canadian electrical grid to offer steel with significantly reduced emissions, but current production of low embodied carbon steel is very limited. Conventional basic oxygen furnaces use an enormous amount of energy and consequently account for approximately 7% of global emissions.[51] Although steel is 100% recyclable, which enables continuous use of the material once mined and refined, there are a number of barriers to effectively achieve this low-carbon potential: the supply of recycled steel cannot meet the demand for new material (50% of global steel production will require virgin material through 2050),[52] recycling and re-rolling steel consumes significant energy, and not all steel can be recycled (reinforcing bars in particular).[53]

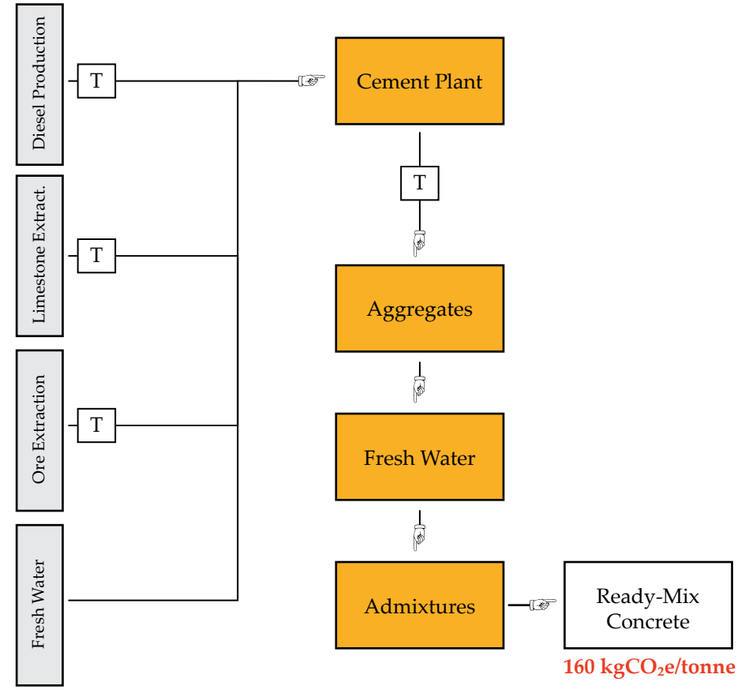
Concrete

Abundantly used globally, concrete constitutes half of all material usage, excluding water.[54] Cement, which serves as the binder for the aggregates in concrete, accounts for only 10%-15% of the volume of concrete but nearly 90% of its embodied carbon. Due to the high temperatures needed to calcify limestone and clay, the manufacturing of cement alone accounts for 8% of global emissions and is on pace for a 50% increase in annual production by 2050 (figure 1.09).[55] Fortunately, there are four main methods of reducing the carbon in concrete: recycled concrete aggregates (less virgin material required), high strength concrete (less total concrete used), low-carbon cementitious binders (reduced cement emissions), and supplementary cementitious materials (less cement used).[56] Fly ash (a coal byproduct) and granulated blast-furnace slag (a steel byproduct) are most widely used to supplant the amount of cement used, due to their low cost and availability (although as coal-fired power plants are phased out, this will increase concrete emissions).[57] Further, most concrete in Canada is reinforced with steel with volumes ranging between 1%-4% of the concrete member. The result is that reinforcing accounts for between 23%-55% of the total embodied carbon of reinforced concrete.[58]

50. Morfeldt, Nijs, and Silveira, "The Impact of Climate Targets on Future Steel Production – an Analysis Based on a Global Energy System Model."
51. Cornwall, "Steel Industry Emissions Are a Big Contributor to Climate Change. Can It Go Green?"
52. Morfeldt, Nijs, and Silveira, "The Impact of Climate Targets on Future Steel Production – an Analysis Based on a Global Energy System Model."
53. Golder Associates Ltd. and Thorn Associates, "Canadian Steel Industry Energy & Greenhouse Gas Emissions Intensity, Technology and Carbon Reduction Roadmap."
54. Circle Economy Foundation, "Circularity Gap Report 2024."
55. Monteiro, Miller, and Horvath, "Towards Sustainable Concrete."
56. Chen et al., "Reducing Embodied Carbon in Concrete Materials."
57. American Coal Ash Association, "The U.S. Fly Ash Market: Production and Utilization Forecast."
58. Sheng et al., "Assessing Embodied Carbon for Reinforced Concrete Structures in Canada."



f 1.08
Simplified embodied carbon flowchart for steel products.



f 1.09
Simplified embodied carbon flowchart for concrete.

Embodied Carbon and Housing

The Missing Middle and Mid-Rise Housing

Missing middle housing refers to a range of low- and mid-rise residential building types, typically containing multiple units, that provide density in a scale compatible with detached, single-family homes (figure 1.10). Once common across Canada, this typology remains prevalent across Europe, some parts of Asia, and historic city centers in North America. Due to overt racial and economic discrimination enforced through the regulatory streams of zoning by-laws and building code, this housing type has been incredibly challenging to build in Canada since the early 20th century.[59] [60] These restrictive regulations, which have shaped the way Canadian cities have developed in the last century, have led to systemic inequity, unaffordable prices, and carbon intense buildings caused in part by a misalignment between legal and desired housing types.[61] [62]

Coined by architect Daniel Parolek,[63] the term "missing middle" has generally been co-opted to refer almost exclusively to multi-unit buildings not more than 3 storeys tall[64] - unsurprisingly in alignment with the Part 9 limits in the NBCC.[65] Mid-rise buildings on the other hand, are more difficult to define, typically encompassing anywhere from 4-12 storeys. This thesis focusses on building types from 3-6 storeys as its main focus, given their carbon efficiency, housing efficiency, and contribution to the public realm.[66] [67]

The Embodied Carbon of Form and Typology

Research suggests that missing middle and mid-rise housing tends to be the most carbon efficient typology as a result of a number of factors (figure 1.11).[68] [69] [70] From a geometric point of view, they hold the most potential for optimal surface area to volume ratios,[71] maximizing the floor area per unit of wall and roof area which, in turn, optimizes both embodied carbon (the enclosure is relatively high carbon) and operational carbon (less area for heat transfer). Further, they present strong housing efficiency, both in terms of

59. Dennis, "'Zoning' before Zoning."
60. Li Bidlingmaier, "Gentrification through Housing."
61. Pomponi et al., "Decoupling Density from Tallness in Analysing the Life Cycle Greenhouse Gas Emissions of Cities."
62. Bozikovic, Case, and Lorinc, *House Divided*.
63. Opticos Design, "What Is Missing Middle Housing?"
64. Jeff Evenson, Ariana Cancelli, and Keir Matthews-Hunter, "What Is the Missing Middle?"
65. Canadian Commission on Building and Fire Codes, "NBCC 2020."
66. Pomponi et al., "Decoupling Density from Tallness in Analysing the Life Cycle Greenhouse Gas Emissions of Cities."
67. Rankin et al., "Embodied GHG of Missing Middle."
68. Doran, "Why We Need Embodied Carbon Benchmarks and Targets in Building Standards and Policies."
69. Zizzo and Doran, "Regulating Embodied Emissions of Buildings: Insights for Ontario's Municipal Governments."
70. Rankin et al., "Embodied GHG of Missing Middle."
71. Straube, *High Performance Enclosures*.

bedrooms/m^2 of floor area and land area, enabling efficient buildings and dense urban environments.[72] These housing types also tend to have the most potential for regulatory and design decisions to impact embodied carbon, and the relatively low fire risk allows for the opportunity to broaden restrictions to further reduce the embodied carbon of these typologies.

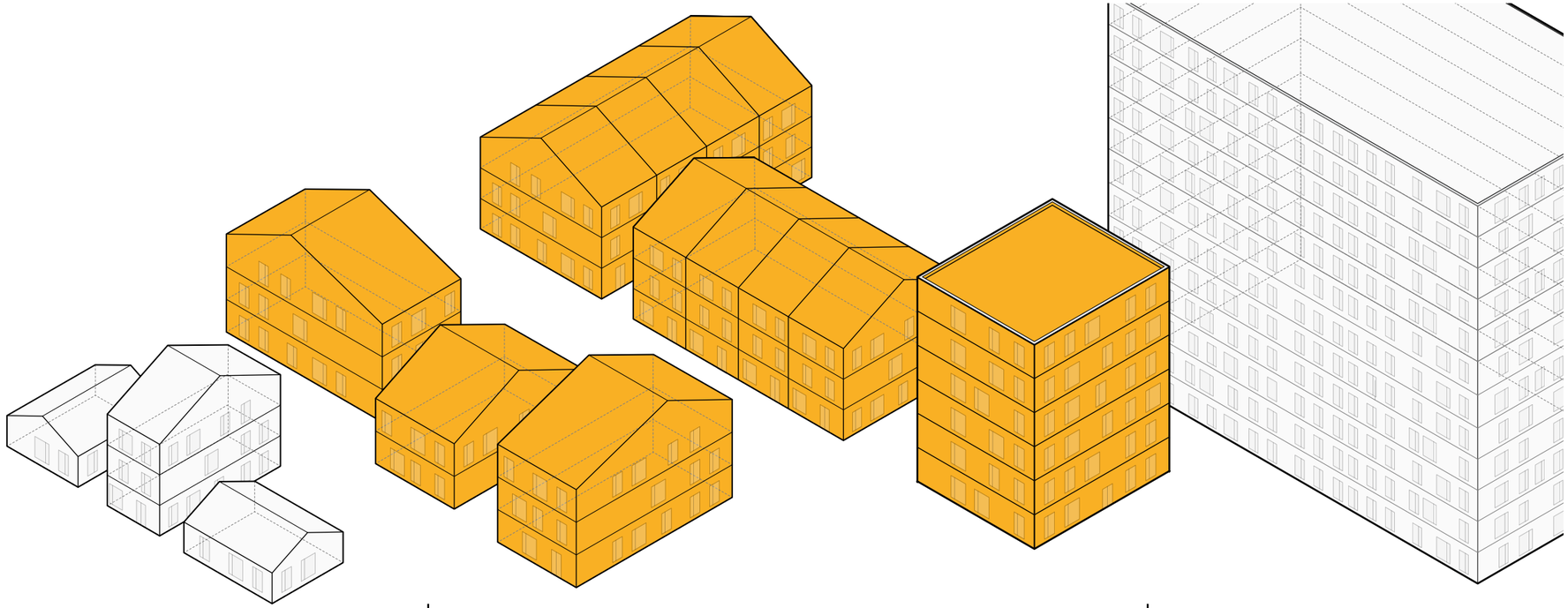
In a study comparing the missing middle with single family and high-rise buildings, researchers found that while emissions ($kgCO_2e/m^2$) generally increase with the number of storeys, missing middle housing has only 75% of the emissions per bedroom, indicative of its middle ground of material consumption and density.[73] However, not all typologies considered in the missing middle are carbon efficient; the difference between the lowest and highest emitting missing middle building was 34,100 $kgCO_2e$/bedroom, a margin which adds caution to the premise that the typology is inherently lower carbon. Further, it highlights the importance that formal and material decisions have on total embodied carbon. The fluctuation of values in missing middle buildings is especially prescient because, although mid- and high-rise buildings have more carbon per bedroom on average, the variation of intensities is significantly less apparent.

Materially, embodied carbon is driven largely by concrete foundations which accounts for approximately 41% in single family homes, 33% in missing middle houses, and 27% in mid- and high-rise buildings.[74] Though concrete makes up the bulk of these emissions, insulation and waterproofing make up approximately one third. Similarly, research highlights the importance of using timber as the primary structural system; steel framing accounts for 26% of emissions, while wood framing only contributes 2% to their respective buildings. Other materials that drive emissions in low-rise buildings include: sub-grade structural concrete, brick cladding, insulation, metal finishes, and gypsum board (drywall). These account for between 40% and 60% of total emissions.[75]

Embodied Carbon Intensity

A number of embodied carbon studies conducted in Canada have provided a range of embodied carbon intensities for housing. This is due to the differences in the studies' spatial, temporal, regulatory, and research scope (e.g. does the study account for interiors?), as well as researcher variability. Rarely do these studies include missing

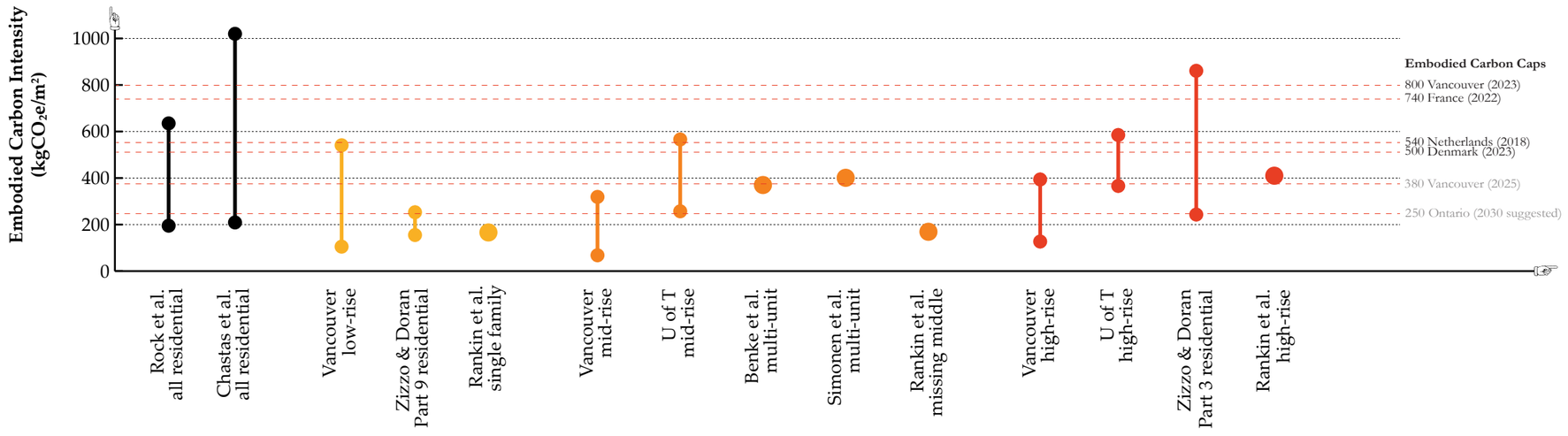
72. Pomponi et al., "Decoupling Density from Tallness in Analysing the Life Cycle Greenhouse Gas Emissions of Cities."
73. Rankin et al., "Embodied GHG of Missing Middle." 12,700 vs approximately 17,000 $kgCO_2e$/bedroom.
74. Rankin et al.
75. Rankin et al.



f 1.10

Missing middle and mid-rise typologies.

It is important to note that definitions for both missing middle and mid-rise vary by publication and that the forms identified in the diagram refer to the typologies that are focused on in this thesis.



f 1.11

Overview of embodied carbon intensities of housing typologies and embodied carbon limits.

Although fairly subtle, there is a clear trend of increasing embodied carbon with increasing height.

middle as a typology, typically lumping it in with the broader category of low-rise residential. Further, most studies report on the carbon intensity of floor area ($kgCO_2e/m^2$) in order to compare projects of different scales. There are a number of alternatives to this functional unit which allow greater comparison of the housing typology. This thesis primarily uses $kgCO_2e$/bedroom and $kgCO_2e/m^2$ as it enables not just the comparison of the embodied carbon of buildings, but the embodied carbon as it relates to the number of people housed. Other units include $kgCO_2e/m^2$/year, $kgCO_2e$/housing unit, and $kgCO_2e/m^2$ of land area (figure 1.12).

A 2023 study of embodied carbon emissions of three building typologies (30-storey high-rise, 6-storey mid-rise, and 3-storey low-rise townhomes) in Vancouver was completed to determine appropriate emission reduction thresholds.[76] The parametric study evaluated all possible combinations of typical materials and assemblies to measure the range of potential embodied emissions (n=700,000). It found that the range of possible emissions were 97-424 $kgCO_2e/m^2$ for high-rise, 38-349 $kgCO_2e/m^2$ for mid-rise, and 75-571 $kgCO_2e/m^2$ for low-rise. The order of magnitude range of values indicates the potential of emission reductions possible within each category, while the upper and lower limits provide a strong argument for the differences between them. Similarly, research conducted by University of Toronto students identified a range of embodied carbon for existing or in-construction apartments (n=10), with a range of 366-615 $kgCO_2e/m^2$ for high-rises (498 $kgCO_2e/m^2$ average) and 227-596 $kgCO_2e/m^2$ for missing middle and mid-rises (349 $kgCO_2e/m^2$ average).[77] A study of multi-unit residential buildings in California (n=8) suggests a value of approximately 370 $kgCO_2e/m^2$.[78] The study builds on a database of over 1000 buildings which suggests that multi-unit buildings (n=75) have an intensity of approximately 401 $kgCO_2e/m^2$.[79] A systematic literature review of 54 studies (not reviewed above) suggests a range of 165-665 $kgCO_2e/m^2$ for all residential buildings (n=186).[80] Another literature review found a range of 179-1050 $kgCO_2e/m^2$ (n=95), although it too does not distinguish between scales.[81] More relevant to the Canadian residential context, a review of Part 9 buildings (n=503) showed a range of 125-283 $kgCO_2e/m^2$ (191 $kgCO_2e/m^2$ average) while Part 3 buildings (n=15) had a range of 213-891 $kgCO_2e/m^2$ (389 $kgCO_2e/m^2$ average).[82] A very recent study by Rankin, Arceo, Isin, and Saxe, shows that single family buildings (n=41) have an average of 146 $kgCO_2e/m^2$, missing middle housing (excluding laneway suites) (n=39) have 169 $kgCO_2e/m^2$, and high-rise apartments (n=22) have approximately 410 $kgCO_2e/m^2$ (figure 1.11).[83]

76. Morrison Hershfield, "Embodied Carbon Reduction Study – City of Vancouver."
77. Doran, "Why We Need Embodied Carbon Benchmarks and Targets in Building Standards and Policies."
78. Brad Benke et al., "The California Carbon Report: An Analysis of the Embodied and Operational Carbon Impacts of 30 Buildings."
79. Kate Simonen et al., "Embodied Carbon Benchmark Study: LCA for Low Carbon Construction."
80. Röck et al., "Embodied GHG Emissions of Buildings – The Hidden Challenge for Effective Climate Change Mitigation."
81. Chastas et al., "Normalising and Assessing Carbon Emissions in the Building Sector."
82. Zizzo and Doran, "Regulating Embodied Emissions of Buildings: Insights for Ontario's Municipal Governments."
83. Rankin et al., "Embodied GHG of Missing Middle,". The authors do not make these values explicit and were calculated by Author based on available information presented.

Sprawl

Research suggests that low-rise, high-density urban environments are the most carbon efficient manner to meet growing demands for urban space.[84] This theoretical research is corroborated by a number of studies which show that dense urban fabric can reduce per capita emissions related to residential heating/cooling and transportation, especially in relation to exurban, and suburban form.[85] [86] [87] [88] [89] Most of these studies account for mode shifts (reduced vehicle use) and operational efficiencies (shared walls in apartment buildings reduce individual heating and cooling loads), but do not consider the embodied carbon reductions that might accompany them (e.g., fewer cars produced, smaller units, reduced HVAC systems).

In 2021, Toronto had 270,000 detached houses and 540,000 apartment units (in buildings with five or more floors) which extrapolates to approximately 1.07 million single family and 738,000 mid/high-rise bedrooms. By substituting in the mean values of missing middle housing for these bedrooms, the city could have saved 9.44 MtCO2e if it had built missing middle buildings instead of the stock that it did. If lower quartile values for missing middle housing were used instead, this number would have been 15.91 MtCO2e. Scaling this shift to Canada as a whole, the government could save 17.75 MtCO2e/year as it works towards the goal of 5.7 million new homes by 2030 - a reduction of nearly 50% compared to current trajectories.[90] These savings are relatively conservative, particularly because they exclude the potential emissions savings associated with density, reduced infrastructure needs, transportation emissions, operational emissions, and land use change.[91]

84. Pomponi et al., "Decoupling Density from Tallness in Analysing the Life Cycle Greenhouse Gas Emissions of Cities."
85. VandeWeghe and Kennedy, "A Spatial Analysis of Residential Greenhouse Gas Emissions in the Toronto Census Metropolitan Area."
86. Jones and Kammen, "Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density."
87. Rauland and Newman, "Why Cities?"
88. Leibowicz, "Effects of Urban Land-Use Regulations on Greenhouse Gas Emissions."
89. Wilson et al., "Blame the Exurbs, Not the Suburbs."
90. Rankin et al., "Embodied GHG of Missing Middle."
91. Rankin and Saxe, "A Future Infrastructure Growth Model for Building More Housing with Less Embodied Greenhouse Gas."

Regulating Embodied Carbon

In general, building codes are intended to provide a baseline level of health and safety, while ensuring affordability. However, as our world and the role of the regulation have become more complex, the NBCC has begun to reach beyond strictly life safety to mandating levels of energy efficiency.[92] The first National Energy Code of Canada for Buildings (NECB) was first introduced in 1997 and aimed to improve the energy efficiency of new buildings and additions.[93] Studies have shown that energy codes can reduce operational emissions by 5%-20%,[94] [95] [96] [97] yet embodied carbon codes lag woefully behind. Low carbon projects tend to be one-off designs which will only have a limited impact if caps aren't codified into policy. Currently, voluntary standards dominate the global approach to embodied carbon regulation in the absence of national policies, although the number of governments and institutions with embodied carbon requirements is growing and the quantitative tools to measure it are improving; signs that change is imminent.

International Approaches

As expected, there is a broad range of approaches to embodied carbon worldwide (figure 1.13). A literature review of national policy was conducted in December of 2023 with the aim of contextualizing the contemporary embodied carbon regulatory landscape. The following summary of international approaches draws on research from Skillington et al. [98] and Curmi et al. [99] as well as foreign government sources. The USA, [100] New Zealand, [101] Singapore, [102] and Ireland[103] all show general governmental support for reducing embodied carbon but have no measurable goals or action plans. Finland,[104] Norway, [105] Germany, [106] Switzerland, [107] and the UK[108] are preparing for embodied carbon limits in some manner; national EPD databases, mandatory LCAs for government buildings, and in-progress legislation. Sweden has proposed embodied carbon caps for 2025 with further limits to be introduced in 2027. [109] [110] The caps are determined by use, ranging from 460 to 180 $kgCO_2e/m^2$, and are to be tightened every 5 years. Effective 2023, Denmark

92. McFarlane, Li, and Hollar, "Building Codes."
93. Canadian Commission on Building and Fire Codes, "National Energy Code of Canada for Buildings: 2020."
94. Li, Rowe, and Wild, "Energy Code Effectiveness on GHG Emission Mitigation for Single-Family Houses in Canada."
95. Chirarattananon et al., "Assessment of Energy Savings from the Revised Building Energy Code of Thailand."
96. Evans, Roshchanka, and Graham, "An International Survey of Building Energy Codes and Their Implementation."
97. Jacobsen and Kotchen, "Are Building Codes Effective at Saving Energy?"
98. Skillington et al., "A Review of Existing Policy for Reducing Embodied Energy and Greenhouse Gas Emissions of Buildings."
99. Curmi, Weththasinghe, and Tariq, "Global Policy Review on Embodied Flows."
100. "Fact Sheet: President Biden Signs Executive Order Catalyzing America's Clean Energy Economy Through Federal Sustainability."
101. "Aotearoa New Zealand's First Emissions Reduction Plan: Building and Construction."
102. "Singapore Green Building Masterplans."
103. "Climate Action Plan 2023."
104. Kuittinen and Hökkinen, "Reduced Carbon Footprints of Buildings."
105. "NS 3720."
106. "Evaluation System - Sustainable Building Assessment System (BNB)."
107. "Koordinationskonferenz der Bau- und Liegenschaftsorgane der Offentlichen Bauherren."
108. Mayhew, Carbon Emissions (Buildings) Bill.
109. "Climate Declaration for New Buildings."
110. "Limit Values for Climate Impact from Buildings and an Expanded Climate Declaration."

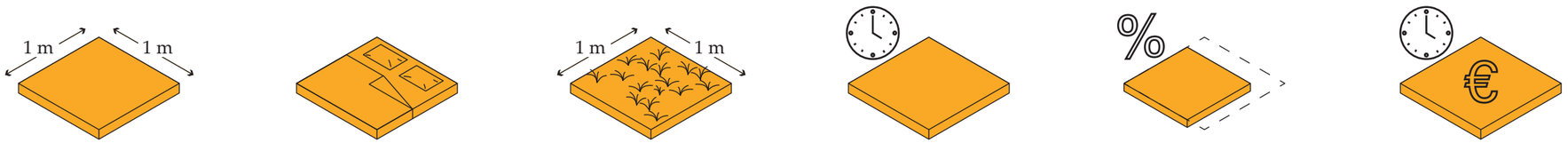
requires all new construction to perform an LCA, while setting limits to embodied energy of all new construction over 1000 m^2. [111] [112] Smaller buildings will have limits set in place in 2025. The initial limit will be 12 $kgCO_2e/m^2$/year (equivalent to 500 $kgCO_2e/m^2$) and decreased to an anticipated value of 7.5 $kgCO_2e/m^2$/year (equivalent to 375 $kgCO_2e/m^2$) in 2029. Similarly, France set whole life carbon limits in 2022, targeting 160 $kgCO_2e/m^2$ for single family housing and 560 $kgCO_2e/m^2$ for multi-family buildings (reducing to 260 $kgCO_2e/m^2$ in 2028).[113] Conducting an LCA and reporting whole life carbon along with embodied carbon for buildings larger than 100 m^2 has been a requirement in the Netherlands since 2018. [114] [115] The 11 metrics measured in the LCA are converted into a single theoretical monetary cost that would be needed to offset the environmental impact; current regulations allow for €0.8/m^2/year (approximately 540 $kgCO_2e/m^2$, based on a cost of €75/tCO_2e and 50-year life) for housing.

Within Canada

Canada fits in with the second grouping of countries; there are some embodied carbon regulations with limited scope, but broad scale regulation is coming. The 2025 NBCC will include operational carbon standards and the 2030 update is expected to expand these standards to embodied carbon as well.[116] The barriers identified by this thesis work under the expectation that embodied carbon caps will be implemented, which in turn justifies the reconsideration the performance of fire safety requirements under the pressure of an additional objective.

At a local level, the Vancouver Building By-law, requires that Part 3 new construction projects complete an LCA which must not exceed 800 $kgCO_2e/m^2$ or a functionally equivalent baseline. Effective 2025, the limits are being tightened to 380 $kgCO_2e/m^2$ or 10% less than the functionally equivalent baseline.[117] [118] The City of Toronto is headed down a similar path; effective 2023, city-owned buildings must have an upfront embodied carbon intensity (A1-A5) below 350 $kgCO_2e/m^2$. This benchmark is in response to the inclusion of voluntary embodied carbon targets within the Toronto Green Standard (TGS) with tiers set at 350 and 250 $kgCO_2e/m^2$, with mandatory embodied carbon caps in development for TGS version 5.[119] Similarly, effective 2025, federal government projects must reduce the embodied carbon of structural elements in major construction projects by 30%

111. "National Strategy for Sustainable Construction."
112. Laue, "How Denmark Leads the Way in Decarbonising the Construction Industry."
113. "Réglementation environnementale RE2020."
114. "MilieuPrestatie Gebouwen - MPG."
115. "Economic Assessment of Projects with High GHG Emissions."
116. Evan Saunders, "National Building Code to Include Two Major Green Building Changes."
117. "City of Vancouver Embodied Carbon Guidelines."
118. "Vancouver Building By-Law 2019."
119. "PH3.19 - Toronto Green Standard Update: Advancing Net Zero Emissions in New Development."



Embodied Carbon Intensity
$kgCO_2e/m^2$

Embodied Carbon Per Bedroom
$kgCO_2e/bedroom$

Embodied Carbon Density
$kgCO_2e/m^2$ of land

Yearly Carbon Intensity
$kgCO_2e/m^2/year$

Percent of Baseline
% of $kgCO_2e/m^2$

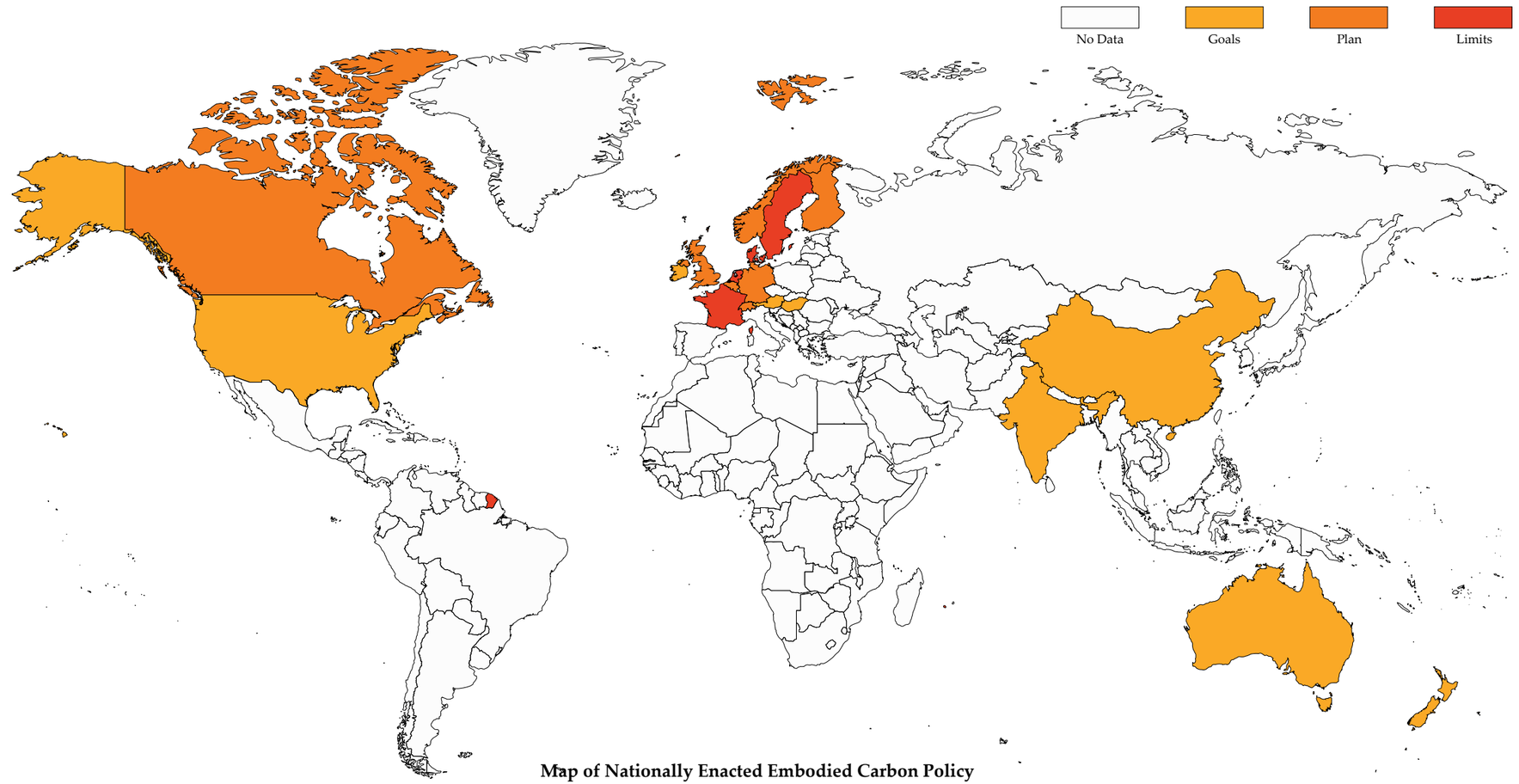
Yearly Shadow Cost
$€/m^2/year$

f 1.12

Measurement units for embodied carbon.

Each measurement unit has distinct advantages and disadvantages however embodied carbon intensity is used by the overwhelming majority of policies and literature.

Methods for Measuring Embodied Carbon



Map of Nationally Enacted Embodied Carbon Policy

f 1.13

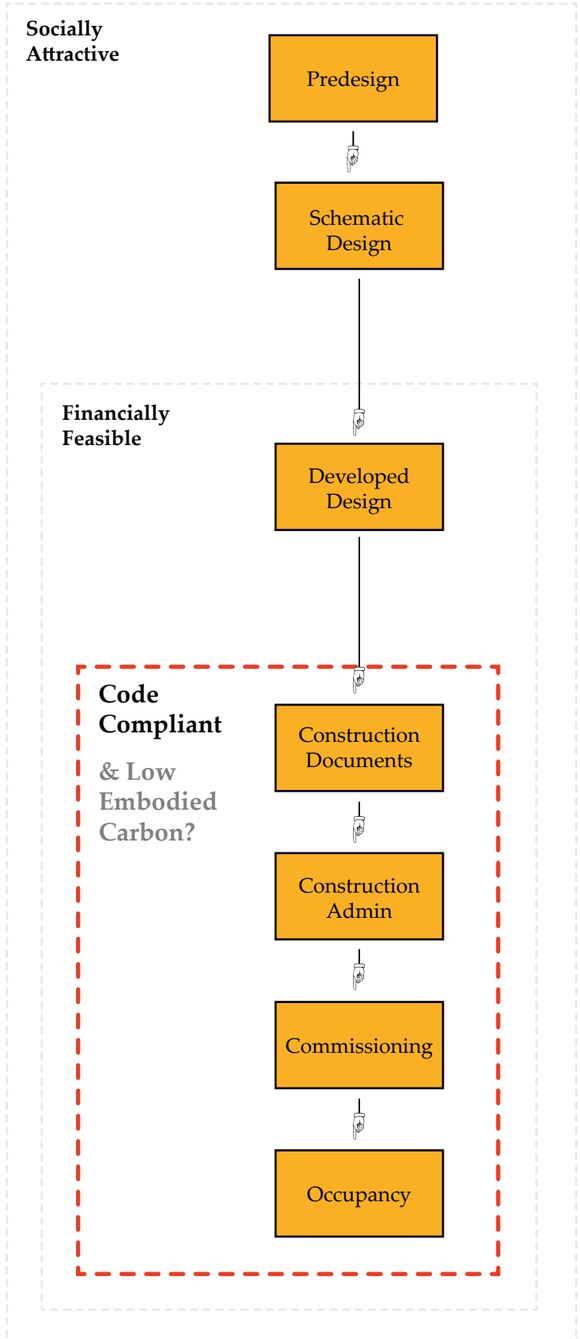
Map of nationally enacted embodied carbon policy.

The literature used to create this map has a distinct lack of data on the global south. This omission is not meant to suggest that there are no embodied carbon policies planned or in action.

based on the industry average EPD and conduct whole building LCAs for major buildings and infrastructure projects.[120] Research around embodied carbon limits suggests that the imminent NBCC requirements may be stricter than current municipal requirements. 50th percentile emissions (approximately 200 $kgCO_2e/m^2$ for mid-rise buildings) are readily achievable through "some care in the design of any concrete used and careful use of foam insulations."[121] Further, a limit of 250 $kgCO_2e/m^2$ by 2030 for all Part 3 residential buildings has been suggested for Ontario (figure 1.11).[122] Both studies found that these limits would have negligible impacts on cost and in some cases would result in modest cost savings as compared to the baseline design.

Decarbonizing Canada's built environment will require acute attention to both embodied and operational carbon to meet climate goals and avoid catastrophe. Embodied carbon however, has received less attention and research than operational carbon, and may have a significantly larger impact on carbon reduction in the short- to medium-term.[123] Owners, developers, architects, engineers, builders, manufacturers, and governments all have a role to play in enabling this reduction of carbon. Many policy pathways have been identified in order to reduce embodied carbon; however, they tend to take a top-down approach without considering the limits of reduction possible within existing frameworks.[124] While financial, procurement, and zoning requirement changes may be effective solutions, they will only get us part of the way there – the solution to embodied carbon is more complex and requires solutions which identify the complete picture, particularly those that empower and enable lower carbon design.[125] Including an embodied carbon limit in the NBCC is an important first step to ensuring that all buildings consider their carbon impact. Pursuant to this, it is imperative that the framework and underlying considerations of the NBCC enable designers to meet and exceed these targets. More than a legal requirement, the Code is the design ethos that all buildings in Canada must ultimately comply with (figure 1.14).

120. "Greening Government Strategy."
121. Morrison Hershfield, "Embodied Carbon Reduction Study – City of Vancouver."
122. Zizzo and Doran, "Regulating Embodied Emissions of Buildings: Insights for Ontario's Municipal Governments."
123. Newmarch, "Embodied Carbon."
124. Panu Pasanen et al., "City Policy Framework for Dramatically Reducing Embodied Carbon: 52 Detailed Policies to Reduce Embodied Carbon."
125. Pomponi and Moncaster, "Embodied Carbon Mitigation and Reduction in the Built Environment – What Does the Evidence Say?"



f 1.14

RAIC phases of an architecture project with the NBCC as the underlying design ethos of Canada.

Low embodied carbon design currently only exists in the realm of the socially attractive (through client briefs) or through financial feasibility (through reduced cost). However, in both cases, these savings are apt to be lost unless the legal minimum includes embodied carbon considerations.

Part Two:
The National Building Code of Canada

Regulatory Frameworks

Building codes are the set of rules which govern the design and construction of structures within an area governed by an Authority having Jurisdiction (AHJ). They tend to be legal documents which aim to achieve broad goals by requiring compliance with a set of regulations. Typically, these goals are "safe" and "economical", although it is critical to note that these objectives vary and have changed over time. In Canada, building codes are derived from the National Building Code of Canada (referred to as NBC by the Code itself but referred to as NBCC by this text for clarity), legislated provincially, and enforced municipally (figure 2.01).[126]

The provincial and territorial governments were bestowed the authority of building regulation by the British North America Act in 1867, however the responsibility to develop and uphold rules for new construction was delegated to municipalities for nearly 100 years. This regulation strategy meant that the quality and consistency of building codes in Canada varied greatly, and in many parts of the country, were nonexistent. The mess of disparate codes during the 1930s demanded a model set of requirements that could be referenced across the country to promote uniformity within the field. Although the history of the NBCC predates even the BNA Act, it was under these conditions that its first iteration was published in 1941. Although nearly all aspects and considerations which influence the Code have changed since its inception: building materials, construction techniques, fire detection and suppression technology, firefighting capability, development methods, and perhaps most importantly, social risk acceptance and objectives of the code, its core tenets remain largely untouched (figure 2.02).[127]

In order to understand the contemporary Code, an evaluation of its development is essential (figure 2.03). The difference in materials, risks, and fire safety at the time of the Codes introduction and development allows for a critical re-examination of these limits in the context of the contemporary world to better suit modern goals. Historically, building regulations have been developed in response to significant events or conditions which highlight specific issues in building design or construction.[128] The findings in the wake of these

126. Archer, "A Brief History of the National Buildings Code of Canada."

127. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

128. Calder and Senez, "A Historical Perspective on Building Heights and Areas in the British Columbia Building Code."

events are condensed into a legal format often without a full review of the implications to existing policies, adding to an ever-growing number of restrictions. The impetus for the new regulations is typically a politically motivated process regardless of its scientific basis.[129]

This section traces the development of the NBCC back to its roots and distinguishes four distinct eras of building code development: the early regulations, the development of fire insurance, the introduction of model building codes, and contemporary regulations. Each period is characterized by the primary concern that the codes aim to address and by their method of addressing that concern. Codes first arise in order to prevent city-wide conflagrations, gradually shift to preventing property damage, and eventually become concerned with life safety, first of workers and later, of the public. The research relies on extensive research conducted by Calder and Senez to provide the base of knowledge. It also incorporates a number of other texts to support and corroborate the novel interpretation and illustration (figure 2.02) of shifting primary concerns due to the influencing factors in the NBCC's development.

The problem of understanding building regulation was described succinctly by R. S. Ferguson, the Head of the Building Standards Section of the National Research Council (NRC) in 1974:[130]

> *In the broadest sense, building regulations develop from contingency to contingency. Each one represents an emergency measure taken with very little or no study. As the emergency recedes, the regulation tends to form part of traditional practice. It is added to the pile, which grows and grows.*

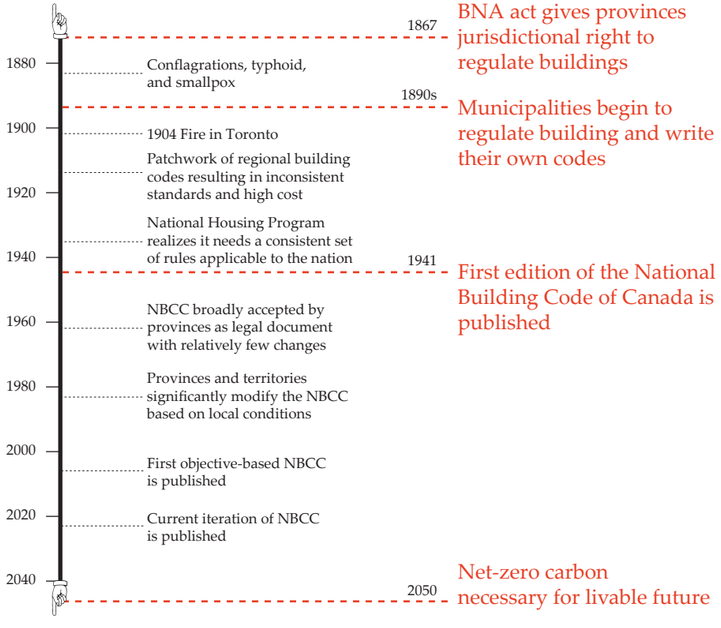
129. Fischer, "Societal Decision-Making for Optimal Fire Safety."

130. Ferguson, "Building Regulations."



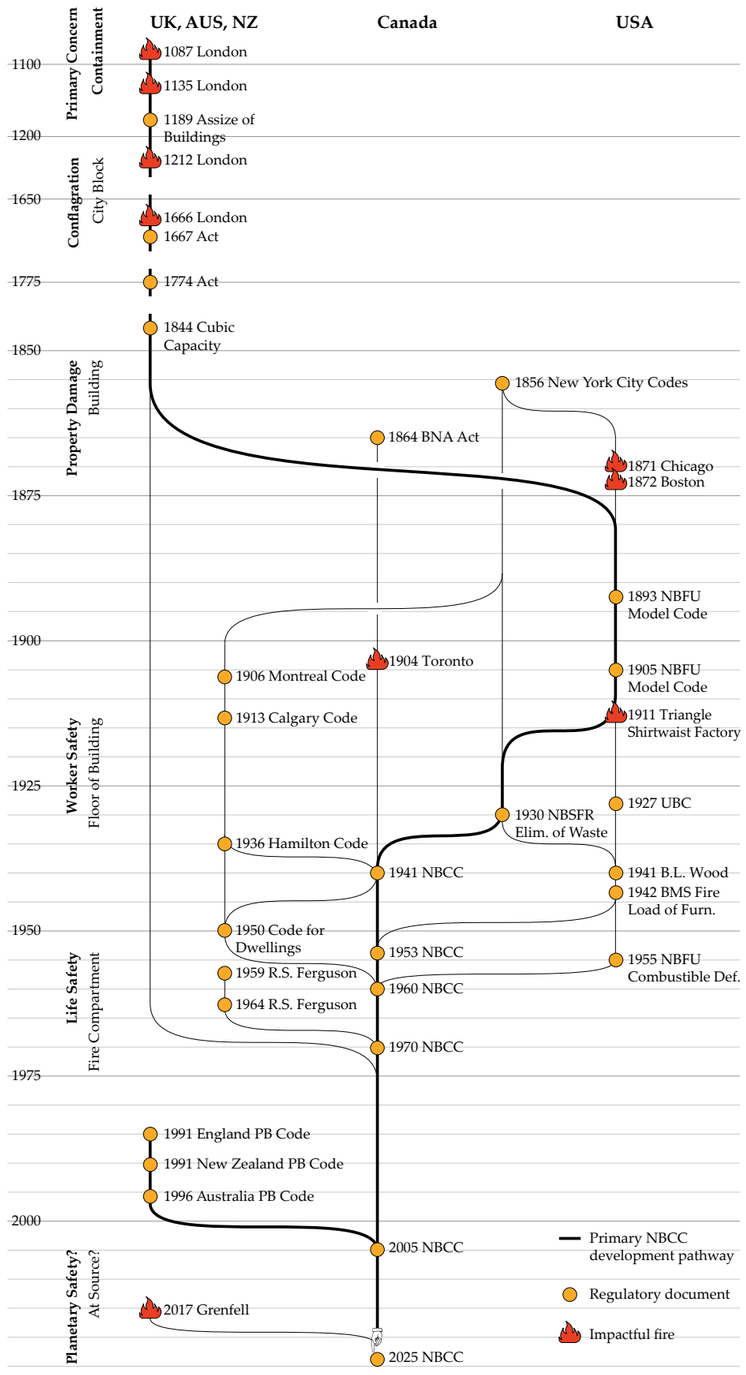
f 2.01

Flowchart of the application of building codes in Canada.



f 2.02

High-level timeline of NBCC development.



f 2.03

The historical roots of the NBCC.

Based on the model codes published in the USA, the NBCC can trace its origins back to the 11th century. The history of the Code is a complex web of municipal building ordinances, insurance standards, key researchers, and significant fire events.

Early Urban Conflagrations 390 BCE - 1800 CE

Fire is broadly considered the impetus for all architecture; the primitive hut was likely first built around a central fire.[131] The risk that fire posed became particularly apparent in urban settings and provoked regulation to keep the danger at bay. Early building code and fire safety protocols can be characterized broadly by their relatively limited regulatory power, litigious power, and firefighting ability. AHJs had limited authoritative reach and very little ability to evaluate the fire safety of individual buildings or urban configurations from a scientific perspective. Consequently, regulations are broad, poorly defined (open for interpretation), and rely on specifying specific construction materials, building separations, and heights.[132] The primary risk of this time period, which codes aimed to mitigate, was city-wide conflagration as the result of dense inhabitation, hazardous industry throughout the city, readily combustible material, and little or no firefighting capability. The Code of Hammurabi (c. 1750 BCE) (figure 2.04) is often incorrectly cited as the first building code[133] [134] (it is certainly a criminal code),[135] however, given the difficult task of distinguishing the first instance of building regulation, this section begins with the Gauls burning Rome in 390 BCE and concludes around 1800 CE as the general protection of the city gave way to fire containment within an individual building.

Rome and the Birth of Building Regulation

The Eternal City has had a fraught history with fire, understandable given its age, but Rome has persevered and been rebuilt time and time again. Following the invasion and subsequent burning of Rome by the Gauls in 390 BCE, Romans returned to their city and rebuilt its dense fabric with a combination of tufa and wood. The abundant tufa construction did not stop the spread of large city fires which occurred in 213, 211, 192, and 50 BCE. The city was still in the process of rebuilding when Augustus became emperor in 27 BCE. He issued one of the first building regulations in relation to fire in 18 BCE which limited building heights and minimum wall thickness in response to the dangers of conflagration.[136]

131. Zografos, Architecture and Fire.
132. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."
133. Baum, "What Are Building Codes?"
134. Burby et al., "Building Code Enforcement Burdens and Central City Decline."
135. Ferguson, "Building Regulations."
136. Strabo, Geography, Volume V: Books 10-12.



f 2.04

Stele of the code of Hammurabi.

unknown, Code de Hammurabi, Photograph, 225 x 79 x 47 cm, Musee du Louvre, accessed October 25, 2024, https://collections.louvre.fr/en/ark:/53355/cl010174436.

Though the city had burned before, and burned after, the fire which occurred in July of 64 CE was the "greatest" of them all (figure 2.05). The Great Fire of Rome burned for a total of five days and destroyed 10 of 14 city districts. Rumored to have been started by order of Nero (or even that he had fiddled while the city burned), the emperor blamed the fire on Christians although it likely started in a workshop or store (figure 2.06).[137] In order to guard against future conflagrations Nero issued that,

> *The buildings themselves, to a certain height, were to be solidly constructed, without wooden beams, of stone from Gabii or Alba, that material being impervious to fire. And to provide that the water which individual license has illegally appropriated, might flow in greater abundance in several places for the public use, officers were appointed. And everyone was to have in the open court the means of stopping a fire. Every building, too, was to be enclosed by its own proper wall, not by one common to others."* [138]

The "certain height" was later defined by Trajan to be 60 feet during his reign.[139] Although likely unrelated, the 60 foot limit corresponds very closely to the 18m (6 storey) limit of combustible construction in the 2020 NBCC.

London and the Threat of Fire Spread

Similarly to Rome, London has burned many times. Following the 1087 and 1135 fires, the Mayor of London issued a bylaw named the Assize of Buildings in 1189. It notes that most structures in London at the time of issuance were "*built of wood, and the houses were covered with straw, stubble, and the like. Hence it happened, that when a single house had caught fire, the greater part of the City was destroyed through such conflagration.*"[140] The ordinance emphasized the importance of limiting fire transfer over other methods of control at this moment in time; thatch roofs were highly flammable and, in a fire, directly exposed to sources of ignition through windblown embers.

In response to these issues, the Assize included one of the first sections which would form the basis of party-wall requirements. "*When it happens that two neighbours wish to build between themselves a stone-wall, each of them ought to give one foot and a half of his land; and so at their joint cost they shall build a stone-wall between them, three feet in thickness and sixteen feet in height.*"[141] In combination with other regulations in this note, such as requiring homes to have stone walls and tile roofs, the requirements aimed to reduce the risk of

137. Byles, "Fire and Its Consequences in the City of Rome in Antiquity, 390 BC - AD 410."

138. Tacitus, Complete Works of Tacitus.

139. Tacitus.

140. Corporation of London, Carpenter, and Riley, *Liber Albus*.

141. Corporation of London, Carpenter, and Riley.



f 2.05

The great fire of Rome.

Robert Hume, The Fire of Rome, 18 July 64 AD, 1785, Oil on Canvas, 76 x 93 cm, 1785, Musee des Beaux-Arts Andre Malraux, https://commons.wikimedia.org/wiki/File:Robert,_Hubert_-_Incendie_%C3%A0_Rome_-.jpg.



f 2.06

Nero punishing the Christians (right) for supposedly setting the fire, which was the first instance in a long line of blaming marginalized people for city fires (see Mrs. O'leary in the Chicago Fire).

Henryk Siemiradzki, Nero's Torches (Christian Candlesticks), 1876, Oil on Canvas, 385 x 704 cm, 1876, National Museum in Krakow, https://commons.wikimedia.org/wiki/File:Siemiradski_Fackeln.jpg.

fire spread between houses and thus limit conflagrations. These regulations took a prescriptive and material-specific approach to solving the issue of fire spread. They approached fire control at the material specification level rather than eliminating sources of ignition or increased detection ability. The inferred object of this party-wall requirement was to limit flame spread through the partition between homes and eliminate the ignition of roofing materials when firebrands landed on neighbouring buildings. The regulations assumed the fire-resistive properties of stone and tile through anecdotal experience without confirming this property through testing (which is understandable, given the time period).

The Great Fire of London began on September 2, 1666 (not to be confused with the other significant London fires in 1087, 1135, and 1212) and burned continuously for 4 days, consuming over 13,000 houses, 87 churches, many city buildings, and notably, St Paul's Cathedral (figure 2.07). The damage from the fire was responsible for the development of more comprehensive building regulations and the birth of fire insurance.[142] In the year following the fire, an Act was passed to regulate the rebuilding of London, aptly named "An Act for rebuilding the City of London". The regulations included requirements for types of construction, materials for exterior walls and roofs, occupancy types, building height, and party walls. Height, construction, and party-wall considerations were based upon four types of building defined largely by their location: lanes, streets of note, principal streets, and mansion-houses not on any street or lane.[143] This series of expanded regulations began to appear similar to those in place today. A notable difference is the designation of building construction by its location relative to the urban fabric rather than other buildings as is the current case. There is likely a correlation between the type of street and the distance between buildings; however, by regulating via the former approach, the act is overt in its protection of the city. A 1708 Act further defined the requirements of a party-wall which reinforces the aversion to conflagration:[144]

> *…wholly of brick or stone, and of two bricks thick at the least in the cellar and ground stories, and thirteen inches thick upwards from the foundation quire through all the stories of each house, and eighteen inches above the roof; and that no mundillion or cornish of timber or wood under the eaves shall hereafter be made or suffered in any such new house or houses, but that all front and rear-walls of every house and houses shall be built of brick or stone...*

142. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

143. Great Britain and Pickering, The Statutes at Large from Magna Charta, to the End of the Eleventh Parliament of Great Britain, Anno 1761 [Continued to 1806].

144. Great Britain, An Act for the Better Preventing Mischiefs That May Happen by Fire.



The LONDONERS Lamentation.

Wherein is contained a ſorrowfull Deſcription of the dreadfull Fire which happened in Pudding-Lane, next beyond Fiſh-ſtreet-hill on the ſecond of Septemb. 1666. betwixt twelve and one of the clock in the morning, being Sunday, and continued untill the Thurſday night following: With an account of the King and the Duke of York's indeavours, with ſeveral Peers of the Land, for the quenching of the ſame; Alſo the manner of doing it, and the name of every particular place where the fire did ſtop.

Tune is, When Troy town, &c.

Of water flow from every eye,
Of all good Subjects in the Land;
Mountains of fire were raiſed high,
Which Londons City do command:
Waſte lye thoſe buildings were ſo good,
And Aſhes lye where London ſtood.

Old London that a thouſand years,
the teeth of time could never waſte,
Now to our raftery appears,
in five daies ſpace, tis burnt at laſt;
Waſte lye thoſe Fabricks were ſo good,
And Cinders lye where London ſtood.

The ſecond of September, at
the diſmal hours 'twixt twelve and one;
At mid-night, up the fire gat,
in Pudding-Lane and brightly ſhone;
Our Engines all could do no good,
Till Aſhes lay where London ſtood.

It over-flow'd New Fiſh-ſtreet-hill,
and then gave fire to Canon-ſtreet,
Then through the Lanes, about did whirl,
until it with the Thames did meet,
As if it would have dry'd the Flood,
And left duſt where the River ſtood.

f 2.07

A broadside ballad which gives an account of the 1666 fire in London.

J. Clark, The LONDONERS Lamentation, 1666, Print, 1666, EEBO, https://commons.wikimedia.org/wiki/File:Londoners-Lamentation.gif.

Fire Insurance and the Standard Building 1774 – 1911

Beginning with the 1774 "Act for the further and better Regulation of Buildings, and Party-walls; and for the more effectually preventing Mischiefs by Fire", which governed construction by placing buildings in relation to one another, this era of code regulation expanded on previous developments by increasing the protection of property from fire loss. Consideration for new regulations was largely based on its ability to limit the material and operational losses associated with fire damage. For example, the cubic capacity concept was developed for the express purpose of limiting warehouse fires, not ensuring life safety. Further, during this time worker rights were still relatively weak, and the purpose of insurance was not to protect against workplace injury or death, rather it was for loss of property.[145] This period ended abruptly with Triangle Shirtwaist Factory fire in 1911 that precipitated the move towards life safety.

Many scholars cite the beginning of "modern" fire insurance to the 1835 New York City conflagration which bankrupted most of the local fire insurance industry and highlighted the inherent risk of limited geographic reach of individual firms.[146] [147] Every city was seen as a potential "value vacuum", a tinder box that might go up in flames at any moment and destroy not only the physical capital (property, insured with money) but also the cultural capital (lives and collective culture, uninsurable to some extent).[148] It is important to see the city in this manner, to see it as a collection of capital, of human effort, of collective values. Fire can annihilate the reflection of the culture onto itself that the city serves to create. Though it is easy to see insurance as a money hungry, amoral industry, through the latter part of the 19th century and the first half of the 20th, the fire insurance industry was largely a righteous endeavour of smaller cooperatives. It was their task to understand materials in their milieu and their ability to spread or impede fire.[149]

London and the Cubic Capacity

A subtle but noteworthy shift occurred in an update to the building regulations in 1774 which correlated wall thickness, building occupancy, and height to the building's location relative to

145. Baranoff, "Shaped by Risk."
146. Baranoff.
147. Wermiel, The Fireproof Building.
148. Bobbette, "A Forensics of the Future."
149. Bobbette.

others. Construction materials were limited by occupancy and the distance between the subject building and public roads (or other buildings), such that, with sufficient distance, the type material was not regulated.[150] The 1774 Act introduced the concept of what is now understood as limiting distance which moved the unit of containment from the city block to the building itself. It placed buildings in relation to one another rather than the urban fabric at large and aimed to limit the spread of fire beyond a single building.

Around the same time, the industrial revolution introduced a sudden growth of large warehouse buildings in London at the end of the 18th century. These buildings, which housed machinery, workers, and storage for bulk goods, required large, open floor space. Consequently, fires would grow rapidly and spread through the unbroken floor space unhindered, quickly growing larger than the capacity of the local fire departments. This danger was addressed by the 1844 "Metropolitan Building Act" which established a volumetric limit rather than mandating floor area or height independently; the concept is known as the cubic capacity.[151]

The initial limit of 200,000 cubic feet was likely based upon the 1774 area and height limitations (60' in height and 3500 sf in area, which equates to 210,000 cubic feet)[152], and the 1844 paper by London Fire Brigade Chief, James Braidwood:[153] "*It may be assumed as a general rule, that the intensity of a fire depends, in a great measure, on the cubic content of the buildings; distinction being made as to the nature and contents of the building.*" In this paper, Braidwood identified that the volume of contents in a building is of primary concern when considering the size and intensity of a fire, and that this risk can be further increased or mitigated through the occupancy of a building (figure 2.08). The Act was revised in 1855 to update the cubic capacity and clarify the subdivision requirements for buildings greater than this limit. The cubic capacity was updated to 216,000 cubic feet based explicitly on Braidwood's assertion that a fire department would be able to suppress a fire of this size:[154]

> *With a well organized and properly equipped fire brigade it is found that sixty feet is the greatest height at which a building can be quickly protected, and that the cube of 60, or 216,000 cubic feet, is the largest cubical capacity which can be protected with reasonable hope of success after a fire has once come to a head.*

Braidwood's "cubic capacity" concept denoted a couple of important changes to the perception of fire risk. First, it emphasized the fire

150. Great Britain and Pickering, The Statutes at Large from Magna Charta, to the End of the Eleventh Parliament of Great Britain, Anno 1761 [Continued to 1806].
151. Great Britain, The Metropolitan Buildings Act. 7th & 8th. Vict. Cap. 84. With Notes.
152. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."
153. Braidwood, "On the Means of Rendering Large Supplies of Water Available in Cases of Fire, and on the Application of Manual Power to the Working of Fire Engines."
154. Eyre Massey Shaw, *Fire Surveys*.

department's role in fire suppression and building regulation. The 1855 regulation was the first instance of fire suppression being considered and relied upon during fire scenarios, a consideration that remains codified to this day (although in a distinctly less concrete manner). Second, the concept implied that height (below a certain level) had no bearing on firefighting ability, only total volume. Similar to the first change, limiting building volume regardless of its arrangement continues to govern our buildings.

Braidwood's paper highlights the relative arbitrariness of building regulation, relying on past regulation and whole numbers to define an undoubtedly more complex issue. While difficult to prove, it is reasonable to assume that the relationship between the firefighting capacity and the legal maximum building volume is self-fulfilling. It seems highly likely that Braidwood's fire brigade would be equipped and trained to fight fires in buildings of the maximum legal capacity (and not any larger), thus fulfilling his estimation of his brigade's maximum ability.

Despite the Act, regulations were often ignored in order to increase profits and consequently Braidwood continued to campaign to reduce conflagration risk. One of the risks he warned politicians about was the series of warehouses on Tooley Street which "*once fairly on fire in one floor, will become such a mass of fire that there is now no power in London capable of extinguishing it…*"[155] This street would eventually take Braidwood's life while fighting a fire in 1861. The Tooley Street fire burned for 14 days and caused enough damage to increase insurance rates for warehouses within the UK and the USA.[156]

United States of America and the Impact of Insurance

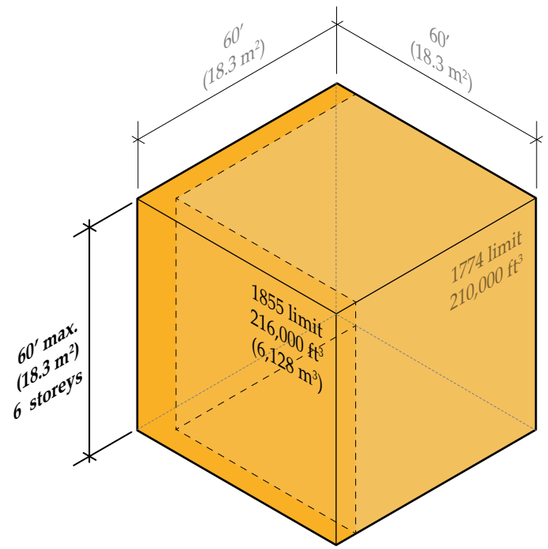
The Great Chicago Fire started on October 8, 1871 and burned for two full days. The devastation was widespread and indiscriminatory, causing approximately $222 million in damages ($5.4 billion USD in 2022) (figure 2.10). A year later, on November 9, 1872, a similar fire ravaged the city of Boston even though a significant portion was built of noncombustible construction (figure 2.11). The close timing and extent of damage led to immense insurance claims, causing many insurance companies to shutter their doors (figure 2.03).[157] The conflagrations highlighted the poor construction standards across the United States as had been noted by UK-based insurers years earlier:[158] "*While some of us were justly priding ourselves on the*

155. James Braidwood, Fire Prevention and Fire Extinction.

156. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

157. Wermiel, The Fireproof Building.

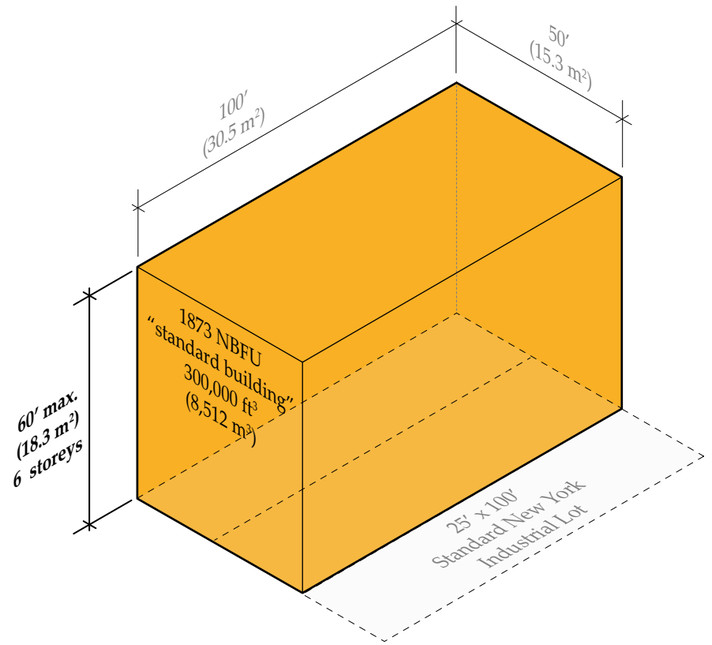
158. Commissioners to Investigate the Great Fire, Report of the Commissioners Appointed to Investigate the Cause and Management of the Great Fire in Boston.



f 2.08

The cubic capacity of a building as defined by London Fire Brigade Chief James Braidwood.

Note that although the dimensions of the building footprint could vary, the 60′ height limit was the maximum height allowed.



f 2.09

The cubic capacity concept as applied by the New York Board of Fire Underwriters to define the "standard building".

It was above this theoretical building volume that additional fire safety measures were required and insurance premiums increased.



f 2.10

View of Chicago after the fire in 1871.

George N. Barnard, Untitled (Chicago after the Chicago Fire), 1871, Photograph, 1871, Art Institute of Chicago, https://commons.wikimedia.org/wiki/File:Attributed_to_George_N._Barnard_-_Untitled_(Chicago_after_the_Chicago_Fire)_-_Google_Art_Project.jpg.



f 2.11

View of Boston after the fire in 1872, an immense scale of destruction despite significant "fireproof" construction.

John Adams Whipple, View from Corner of Washington & Bromfield Streets, 1872, Photograph, 1872, Boston Public Library, https://commons.wikimedia.org/wiki/File:Boston_Fire_from_Washington_%26_Bromfield_panoramic_by_Whipple,_1872.jpg.

elegant architecture of this district, and boasting that is was practically fire-proof, English insurers were dreading a conflagration on this very spot, and preparing to withdraw their agencies from our city."

Following these city fires, the US fire insurance industry noted the importance of establishing a "standard building" which could be used to evaluate relative risk and set rates nationwide. The concept of the "standard building" was to define a basis of fire safety and corresponding insurance rate from which rates could be increased or decreased for a class of buildings or specific building depending upon factors affecting fire risk. This evaluation structure was based upon the idea that every building had different inherent fire risk depending on their characteristics and context. The insurance "schedules" (the insurance industry's manner of evaluating risk) were based upon factors such as height, area, occupancy, type of construction, access (number of streets facing), and sprinklers. The identification and evaluation of the effect of building characteristics on fire risk was primarily based upon observation from actual fires rather than studies.[159]

The increased insurance rates aimed to regulate the building characteristics which increased the potential for a building to become part of a conflagration. The "standard building" defined by the New York Board of Fire Underwriters issued in 1873 was specific to warehouses and storage buildings with a large focus on the fire safety of the building enclosure. These regulations were highly influenced by UK-based insurers and included in this definition, the height limit of 60′ and cubic capacity of 300,000 cubic feet.[160] These values are consistent with a proposed 1874 update to the Metropolitan Building Act mentioned above, and reflect the dimensions that both the London Fire Brigade and New York Fire Department felt they could handle.[161] Conveniently, the 300,000 cubic capacity, codified in 1873, aligned perfectly with the 25′ by 100′ lots of New York City, established in 1811. In combination with city zoning which allowed 100% lot coverage in the warehouse district, this insurance regulation allowed owners to build on two lots (50′ x 100′ footprint) and up to 6 storeys (60′) without any additional premiums (figure 2.09).

In these instances, in both London and New York, the cubic capacity indicated that the building code was not derived independently (as it should in a scientific pretext), but rather in response to, and often in favour of, existing financial and property conditions. If the 216,000 cubic foot capacity had been upheld, property owners would have

159. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

160. Calder and Senez.

161. Freitag, Fire Prevention and Fire Protection as Applied to Building Construction; a Handbook of Theory and Practice.

been forced to either have unutilized space on the second lot, limit their building to one lot (only 150,000 cubic feet), or negotiate with other building owners to fully utilize the space. The conceptual similarities between the two regulations along with underwriter correspondence at the time support the link between the New York policy and London one 30 years earlier:[162] *"[An architect in this city] quoted the authority of the Chief of Brigade in London, for this very statement that 50 by 100 feet was as large a building as he wanted to cope with."*

To determine the insurance rate of a building, the type of construction was broken down into two categories: fireproof and non-fireproof,[163] broadly similar to our current understanding of non-combustible and combustible construction. This distinction was deemed the most important risk factor and subsequent factors (e.g. area) were determined based on which construction type a building belonged to. The allowable area for a fireproof building was twice that of a non-fireproof one, a convenient and simplified approximation of their relative safety rather than any sort of scientific derivation.

Some considerations, such as height and area, had cutoff points where the incrementally increasing rate suddenly skyrocketed or was considered a risk too great to insure. For example, heights greater than seven storeys faced enormous rate hikes as heights greater than this were considered beyond the reach of firefighting services.[164] This rate hike was consistent across fireproof and non-fireproof buildings. This further adds to the argument that fire suppression was the primary method of addressing fire risk at this point in time.

Accessibility and sprinklering, both methods of fire suppression, were other key factors for reducing fire insurance rates. The number of sides that could be accessed by firefighters greatly impacted their ability to reach the source of fire and control its growth. In addition to this, the greater the number of streets a building faced, the lower the risk of flame spreading to adjoining buildings. The importance of sprinklers was much more slowly understood but as the systems increased in reliability, their inclusion in a building permitted in some cases up to 60% reduction in rates.[165] The increase of allowed area in relation to access and sprinklers carried forward all the way into the 1990 NBCC, where the combination of these two factors allowed for a 200% increase in floor area.[166] The importance given to access and sprinklering at this time further emphasizes the approach of limiting fire to a single building to prevent conflagration.

162. Loudon Snowden, "Proceedings of a Convention of Fire Underwriters."

163. Cassier's Magazine.

164. American School of Correspondence, Cyclopedia of Fire Prevention and Insurance.

165. American School of Correspondence.

166. Associate Committee on the National Building Code, "National Building Code of Canada: 1990" (National Research Council Canada, 1992), 70-71.

The insurance rating schedules were not legally binding documents nor were they informed by the public's acceptance of risk; they were business documents meant to maximize profit. Although there were many mutual fire insurance companies whose goals were to reduce insurance rates as much as possible for their members, these were still understood as maximizing profit for those involved in the mutual.[167] The schedules mandated and excluded some types of construction by making them prohibitively expensive to insure which moderated the construction industry and increased building standards in the late 1800s. The purpose of rating schedules was not to define fundamental hazards or morally acceptable risk, they were to determine relative hazard and financially acceptable risk:[168]

> *It is entirely useless to appeal to an individual's love of his city, and of the public weal, to cause him to substantially improve his buildings, for protection against fire, from causes not entirely plain to him; this is true of the majority: it is equally true of the entirety that if you can show them where to save money while benefiting themselves, they will do it; we all go for the great American dollar; and the key to many a man's attention is found in his pocket.*

In combination with stronger insurance companies, labour movements also helped move building regulation forward. On March 25th, 1911, the Triangle Shirtwaist Factory fire killed 146 workers, most of whom were women and children (figure 2.12). The fire, which presumably began in a scrap bin, highlighted an abundance of fire safety issues including locked exit doors (to keep workers from leaving early), inadequate fire escapes, and highly combustible contents (the building itself was unharmed).[169] Though it had a lower death toll than the 1903 Iroquois Theatre fire in Chicago (602 deaths, and had similar fire safety issues), the Triangle Shirtwaist Factory fire was a significant catalyst towards building regulation, especially when the factory owners were acquitted of manslaughter and profited from fire insurance (figure 2.13).[170] A number of Canadian fires also shaped the formation of the NBCC including the 1900 Hull-Ottawa fire (7 deaths, 15000 homeless) (figure 2.14), 1904 Bay Street fire in Toronto (1 death, but more than $2.82 billion in damage) (figure 2.16), the 1918 Grey Nunnery fire (53 deaths, all infants), and the 1927 Laurier Palace Theatre fire (78 deaths, all children) (figure 2.15).[171] [172]

167. Wermiel, The Fireproof Building.
168. Vol. 54, 1895.
169. "141 Men and Girls Die in Waist Factory Fire; Trapped High Up in Washington Place Building; Street Strewn with Bodies; Piles of Dead Inside; The Flames Spread with Deadly Rapidity Through Flimsy Material Used in the Factory."
170. The Editors of Encyclopaedia Britannica, "Triangle Shirtwaist Factory Fire."
171. Donal M. Baird, The Story of Firefighting in Canada.
172. "Fire Safety Design in Buildings."



f 2.12

The Triangle Shirtwaist Factory fire in the Asch Building (now the Brown Building) which still stands at 23-29 Washington Place.

unknown, Triangle Shirtwaist Factory Fire First Published on Front Page of The New York World, March 25, 1911, Photograph, March 25, 1911, University of Cornell, https://commons.wikimedia.org/wiki/File:Image_of_Triangle_Shirtwaist_Factory_fire_on_March_25_-_1911.jpg.



f 2.13

A memorial of 100,000 people attended the funeral for the victims of the fire, leading to stronger labor laws, building regulations, and worker's unions.

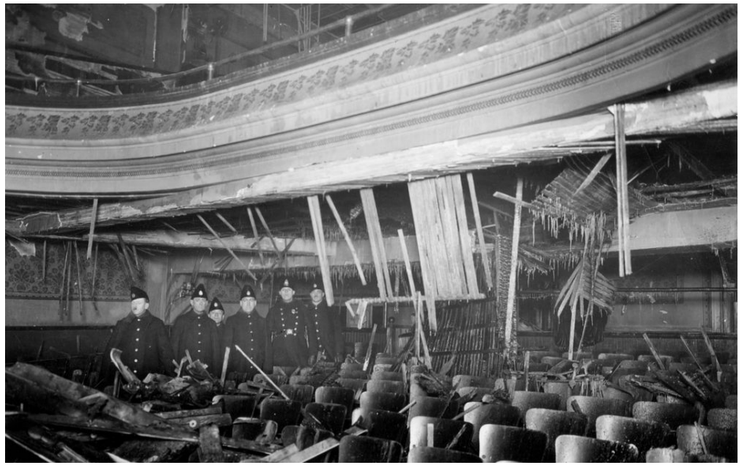
unknown, The Funeral Procession, April 5, 1911, Photograph, April 5, 1911, University of Missouri-Kansas City School of Law, https://famous-trials.com/trianglefire/966-images.



f 2.14

View of Hull–Ottawa fire blowing across the Ottawa river.

unknown, Big Fire of April 26th 1900, April 26, 1900, Photograph, April 26, 1900, Bytown Museum, https://imgur.com/a/EOzrl44.



f 2.15

The aftermath of the Laurier Palace Theatre fire, relatively intact furnishings and structure show the dangers that egress and smoke pose in the event of a fire.

unknown, The Aftermath of the Laurier Palace Theatre Fire, January 1927, Photograph, January 1927, Montreal Gazette Archives, https://montrealgazette.com/news/local-news/history-through-our-eyes/history-through-our-eyes-jan-9-1927-laurier-palace-theatre-fire.



f 2.16

Aftermath of the Toronto fire in 1904, many masonry exteriors of buildings remained standing although their interiors burned out.

unknown, Aftermath of Fire, Wellington St, 1904, Photograph, 1904, Toronto Public Library Archive, https://digitalarchive.tpl.ca/objects/336780/fire-1904-aftermath-of-fire-wellington-st.

Model Building Codes and Worker Safety 1893 – 1960

Following the widespread private adoption of more stringent insurance regulations, many local building ordinances similarly adopted the requirements and codified them into law. These local building ordinances varied significantly from municipality to municipality which caused challenges for larger insurance agencies to evaluate their respective fire risks. This period of code development begins with the early efforts to develop consistent building regulations by insurance underwriters. However, following a series of deadly fires at start of the 20th century, model code development began to include associated professionals and came to the attention of federal US agencies during the 1920s.

In Canada, there was no organization or federal agency suitable to write such a code when it was first considered in 1920. As a result, the hodgepodge of municipal codes remained into the 1930s which resulted in difficult economic conditions that were compounded by the Great Depression.[173] The first NBCC was published in 1941 and cemented the notions of safety, cleanliness, and a minimum standard of living which were synonymous with the postwar ethos. This era of building regulation gradually fades out as funding for the development of the NBCC slows in the 1960s.

United States of America and National Agencies

In response to the Great Chicago Fire a few years earlier, the Fire Ordinance of Chicago of 1875 implemented height, area, and combustibility requirements:[174] "*All buildings henceforth to be erected within the corporate limits of Chicago shall have their walls constructed wholly of incombustible materials.*" Although this version of the ordinance did not define construction types, the 1905 Municipal Code of Chicago did: Ordinary (understood as masonry walls with wooden floor systems), Mill (heavy timber construction where some fire resistance is achieved through increased sizes), and Fireproof (all structural components are made of non-combustible material).

The early municipal codes of the eastern United States precipitated the need for a national model building code in order to streamline

173. Archer, "A Brief History of the National Buildings Code of Canada."

174. Chicago (Ill.), Jamieson, and Adams, *Municipal Code of Chicago*.

construction and regulation. The need for such a code became apparent in the early 1890s, 50 years before Canada. Delegates from the respective national associations of Architects, Engineers, Builders, Building Inspectors, and Underwriters met in 1891 to draft suggested ordinances, and although this early attempt to combine the various city ordinances was unsuccessful, the National Board of Fire Underwriters (NBFU) completed a much more complete model code in 1893.

This 1893 code, published with the purpose of providing building regulations to towns and counties with populations too small to develop their own, was overhauled and republished in 1905 as the First Edition of the NBFU Recommended Building Code, which contained height and area limits based upon occupancy, construction type, sprinklering, and streets facing. The 1905 edition reflected lessons from the fire statistics and construction information that the NBFU had collected from foreign consuls of large cities from across the world. This effort was conducted with "*The ultimate purpose is a reduction of the fire waste of the country…*" and only contained two types of construction: fireproof and non-fireproof.[175] Given that this code was written by the same board that issued the Universal Rating Schedule, fireproof construction was allowed twice the area of non-fireproof construction. Updates to the NBFU model code were issued regularly until 1965.

In 1913, Ira H. Woolson, consultant engineer for the NBFU, issued a report in which he summarized the results of a survey of recommended allowable building heights and areas from fire chiefs across the country (figure 2.17).[176] It is worth noting that these results are in reference to height and area limits of factory buildings, though throughout the report they are generalized as "buildings". Similarly, the definition for storey is not provided, such that the actual height (in meters) may vary significantly. Further, non-fireproof construction was intended to refer to brick and joist construction (known as "ordinary construction" at the time).

The 1915 NBFU code update expanded on the building heights, and notably restricts "frame dwellings and tenements occupied by not more than two families" to 2.5 stories while the same building, occupied by only one family could have a three-storey height. The maximum height that non-fireproof construction was allowed was 5 storeys (65 feet), as this was the furthest that water could be thrown from the street (figure 2.18).[177] Further updates were issued to the code in 1922 and 1934, however height and area restrictions relative to construction type did not change from the 1915 code.

175. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

176. Woolson, "Allowable Heights and Areas for Factory Buildings."

177. National Board of Fire Underwriters, Building Code Recommended by the National Board of Fire Underwriters.

Though seemingly semantic, it is essential to understand that these early codes are based on mercantile and industrial occupancy. The fire risks from these occupancy classes are different than residential, as had already been noted at the time, yet the simplification of factory buildings to "buildings" allows for these relative risks to be obscured.

The National Fire Protection Association (NFPA), established in 1896, was largely composed of representatives from the fire insurance industry. The Committee on Fireproof Construction, Including Concrete and Reinforced Concrete (later changed to "Committee on Fire Resistive Construction" and chaired by Ira H. Woolson) established three types of construction, noting that none were "fireproof" as considered in the NBFU codes. By 1914, the NFPA considered three types of construction: full protection (implies a resistance to severe fire for 4 hours), partial protection (implies a resistance to severe fire for 2 hours), and temporary protection (implies a resistance to severe fire for at least 1 hour).[178] These categorizations are similar to what we would now understand as Fire Resistance Rating (FRR).

Herbert Hoover (Secretary of Commerce at the time) appointed a Building Code Committee in 1921 *"with the object of determining basic requirements that could be recommended to ensure public safety and at the same time promote economy in construction."*[179] This proclamation is one of the more direct examples spelling out the purpose of a building code; the balance between life safety and economic construction. The implication of multiple goals is that there must be compromise in order to meet one goal or another, an ethos which has generally faded with time as regulatory priorities have shifted to life safety.

The Committee prepared six reports as part of the "Elimination of Waste Series" which covered various aspects of building regulation. The sixth report "Recommended Minimum Requirements for Fire Resistance in Buildings" was led by Ira H. Woolson and aimed to provide life safety while guarding against conflagrations. The number of construction types expanded to six and the area limits outlined in this document correspond to the conclusions drawn from Woolson's 1913 survey of fire department capabilities.[180] Nearly 100 years after Braidwood, the same tactic of relying on the experience of firefighters to determine building regulations is practiced – the same buildings which have likely informed their firefighting ability.

A 1942 report by the Subcommittee on Fire-Resistance Classifications published by the National Bureau of Standards in the USA defined

178. National Fire Protection Association, "Proceedings of Eighteenth Annual Meeting."

179. Hatt et al., Recommended Minimum Requirements for Fire Resistance in Buildings.

180. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

Type of Building	Average Storeys in Height	Average Area between Fire Walls in Sq. Ft.
Non-fireproof, not sprinklered	3.1	6,300
Fireproof, not sprinklered	4.9	12,300
Non-fireproof, sprinklered	4.6	12,800
Fireproof, sprinklered	7	27,100

f 2.17

Survey responses from fire chiefs across the USA indicating recommended building heights and areas.

Author's drawing reproduced from: Ira H. Woolson, "Allowable Heights and Areas for Factory Buildings," Transactions of the American Society of Mechanical Engineers 35 (January 1913): 231–37, https://doi.org/10.1115/1.4059921.

Section 37. Height of Buildings.

1. No building, or structure hereafter erected, except church spires, water towers, smoke stacks or chimneys, shall exceed in height two and one-half times the width of the widest street upon which it fronts, nor shall it exceed the following limits:

	Height in Stories.	Height in feet.
Frame buildings used for purposes other than dwellings and tenements.	2	30
Frame dwellings and tenements occupied by not more than two families.	2½	30
Frame dwellings occupied by not more than one family.	3	35
Buildings having bearing walls of hollow terra cotta or concrete blocks.	3	40
Non-fireproof buildings, ordinary construction	4	55
Non-fireproof buildings, mill construction..	5	65
Fireproof buildings used for factories, stores, warehouses or workshops.	7	85
Fireproof buildings used for purposes other than factories, stores, warehouses or workshops	10	125

2. *Non-Fireproof Construction—*

(a). Tenement houses, 3000 sq. ft.

(b). All other ordinary non-fireproof buildings, height not exceeding 55 feet.

Fronting on	Without sprinklers.	With sprinklers, increase of 66⅔ per cent.
One street.	5,000 sq. ft.	8,333 sq. ft.
Two streets.	6,000 sq. ft.	10,000 sq. ft.
Three or more streets.	7,500 sq. ft.	12,500 sq. ft.

f 2.18

Height and area limits in the 1915 NBFU model code, it is interesting to note that a wood frame building with just one family is permitted to be 3 storeys in height, while those with two familys are only permitted to be 2.5 storeys in height, and those with more than two families must be fireproof.

Excerpt from: National Board of Fire Underwriters, Building Code Recommended by the National Board of Fire Underwriters: An Ordinance Providing for Fire Limits, and Regulations Governing the Construction, Alteration, Equipment, Repair or Removal of Buildings or Structures (New York, NY, 1915), https://catalog.hathitrust.org/Record/100395166.

four types of buildings: fireproof, incombustible, exterior-protected, and wood construction. The report also summarized a survey of the combustible content of buildings by occupancy. The results from the residential table show an average of 8.8 lb/ft² which corresponds to a fire severity between ¾ and 1 hour (weights of 7.5 lb/ft² and 10 lb/ft² respectively).[181] The results from this report align with requirements for FRR in the NBCC today (and surprisingly, to fire load of Canadian apartments; 8.8 lb/ft² of wood emits approximately 640 MJ/m², close to the measured values of 393-807 MJ/m²).[182]

Canada and its Slow Beginning

Municipal building codes in Canada in the first part of the 20th century bear close resemblance to American cities of the same period. Although the development method of the NBCC was different than its US counterpart, many municipal codes present lines of regulation similar to the contemporary Code, such as the 1913 City of Calgary By-Law:[183] "*No apartment house of non-fireproof construction shall have an area exceeding 2000 square feet on any floor unless divided by interior division wall of fireproof construction extending from basement to roof.*"

At the same time, work was being completed to translate the UK cubic capacity concept to a Canadian application. John B. Laidlaw outlined considerations to floor area and height limitations in a Canadian context in 1905.[184] The approach assumed the building as the unit of containment for fire and the values proposed align closely to values still present in the 2020 NBCC. Laidlaw briefly discussed this assumption and noted that if the building could be constructed such that a fire would likely be contained to a single floor, then the allowable area limits could be readily increased, an understanding shared by J. Grove Smith, the Dominion Fire Commissioner of Canada.[185]

In 1920, consideration was given to developing a national building code for Canada but was shortly abandoned since there was no organization to develop or administer such a document. This goal was resurrected in the 1930s by construction agencies hindered by mismatched codes.[186] The National Research Council (NRC) formed a committee to investigate the issue in 1932 and organized a conference to write the code in 1937. It was noted that this process had been initiated 30 years earlier in the US, and that "*any building code authority in Canada could do no better than adhere to the procedure followed by American authorities and take advantage of their recommendations.*"[187]

181. Subcommittee on Fire-Resistance Classification, "Fire-Resistance Classifications of Building Constructions."
182. Bwalya et al., "Survey Results of Combustible Contents and Floor Areas in Canadian Multi-Family Dwellings."
183. City of Calgary, 1913 : building ordinances : by-law no. 1366.
184. Laidlaw, "The Conflagration Hazard."
185. Smith, "Fire Waste in Canada."
186. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."
187. Gill, "A National Building Code."

When the 1941 NBCC was published, its contents were highly influenced by the "Elimination of Waste" series which itself was based upon large city building codes and the 1913 Woolson report (which were based on insurance limits set as a result of London firefighting capability) (figure 2.19). Limited change occurred to the NBCC from 1941 to 1948 due to the second world war and a shift of focus to single-family development.[188]

B. L. Wood, part of the American Iron and Steel Institute, published "Fire Protection Through Modern Building Codes" in 1941, which examines contemporary approaches to fire-safe buildings.[189] His approach and methodology outlined in this paper had a significant influence on the development of the NBCC following its first edition.[190] Wood discusses that the 3 or 4 storey height limit, which was generally accepted for combustible construction, was the result of the limit from which a fire can be fought from the street, where other construction types assume that firefighting occurs from the interior of the building. He notes that the relative hazard of one construction type to another is primarily experientially based, and goes on to discuss the "juggling process" through which code limits come to be established: "*Finally, more or less arbitrary values have been selected… the area limitations that appear in building codes often prove inconsistent when studied carefully in the light of existing data on the relative fire hazards involved in the carious occupancies and the relative fire safety afforded by the different types of construction.*"[191] (figure 2.20). This passage makes clear that existing codes at the time of publication had been established in a baseless manner and relative risk created by building qualities has been characterized through perceived risk rather than fire data.

Wood presents four factors to consider in developing area limits: relative fire hazard associated with each occupancy, relative fire hazard of the building structure, construction features which impede the spread of fire, and the number of occupants and their ability to evacuate a building. Notably, when suggesting the relative risk of occupancy and construction types to one another, Wood continues the tradition of using "business" as the base occupancy, but assumes heavy timber as the base construction type.[192] Through the 1950s, various changes were made to the NBCC in order to catch up to American regulations of the previous decades, including occupancy loading, fire loads, and sprinklering. Despite the advances in fire detection, suppression, and material advancements, the height limit was still based largely on firefighting capability: "*4 storeys was the effective limit for fire fighting, [and] fire fighters did not like high fire*

188. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."
189. Wood, Fire Protection Through Modern Building Codes.
190. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."
191. Wood, Fire Protection Through Modern Building Codes.
192. Wood.

loads in tall buildings."[193] Height and area limits were updated in the 1953 NBCC to reflect suggestions outlined by Wood, although there was some disagreement regarding the validity of these new values. Consequently, a number of arbitrary changes were included as compromises to the interests of wood and steel construction.[194] Disagreements on the height and area limitations table delayed the publication of the 1953 NBCC by nearly two years.

193. Advisory Fire Group, Associate Committee on the National Building Code, "Minutes of the Second Meeting of the Panel on Heights and Areas."

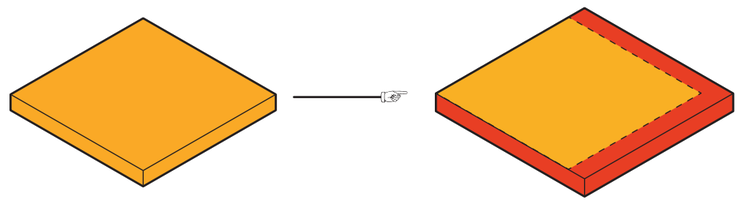
194. Associate Committee on the National Building Code, "Minutes of a Special Meeting Held to Discuss Proposed Table of Height and Area Limitations of Buildings Other Than 1 and 2 Family Dwellings."

Construction Type	1930 NBSFR		1941 NBCC	
	Height (ft) (m)	Area (1000 sq. ft) (m2)	Height (ft) (m)	Area (1000 sq. ft) (m2)
Fire Resistive	30 + 9.1 +	25 + 2323 +	45 + 13.7 +	10 + 929 +
Heavy Timber	55 - 80 16.8 - 24.4	7.5 - 20 697 - 1858	44 - 75 16.8 - 22.9	7.5 - 15 697 - 1394
Masonry and Frame	45 - 55 13.7 - 16.8	5 - 10 465 - 929	35 - 55 10.7 - 16.8	5 - 7 465 - 697
Wood Frame	30 - 35 9.1 - 10.7	3 - 5 279 - 465	20 - 35 6.1 - 10.7	3 - 5 279 - 465
Unprotected Metal	1 storey	unlimited	1 storey	unlimited

f 2.19

Height and Area Limit Comparison of the 1930 NBSFR and the 1941 NBCC.

Author's drawing reproduced from: Keith Calder and Peter Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada" (Sereca Consulting Inc, March 19, 2015).



f 2.20

The growth of allowable building areas as a result of changing units of measure.

Author's drawing. Holding all else equal, this simplified substitution to ease administrative burden increases fire risk by nearly 8%. It further shows the imprecision of defining building limits by simple whole numbers.

Contemporary Fire Safety 1955 – Present

The contemporary era of fire safety and fire safety regulation largely begins in concert with the formation of values post WWII. Large economic and industry shifts were occurring which demanded that the further development of a national document to assimilate construction standards across the country. Early in this period, processes and testing standards were developed and codified to bring a greater scientific basis to the Code. These definitions were employed with the idea that the large-scale categorizations could be used as a transition from prescriptive requirements to performance standards which would not restrict material use provided it met the limits (figure 2.21).

Concurrently, significant advances in fire detection and suppression technology were taking place which had large impacts on fire frequency and severity (figure 2.22). Sprinklering, long accepted as an effective manner to reduce risk and originally incorporated as a manner to protect property and thus reduce insurance rates,[195] has been a part of the NBCC since its first edition although not thoroughly incorporated until 1980.[196] The benefit that automatic sprinklers provide however, has little, or no scientific basis. A 100% increase of building area which was permitted from 1941 until the 1990 NBCC was based on US model codes, who themselves increased the limit from 66% to 100% based on anecdote.[197] In the 1995 NBCC, sprinklering was considered to replace the risk reduction provided by the number of streets a building faced and allowed for up to a 200% increase in building area, which continues to the 2020 NBCC. "A new rationale for reconsidering the underlying height and area of a building should be based on an assessment of current sprinklering capabilities and statistics."[198]

Another important development was the introduction of smoke alarms in the 1977 NBCC.[199] Canadian fire death rates support the case that the integration of this technology in new buildings through policy and old buildings through outreach campaigns significantly reduced the impacts of fire on occupants.[200] Smoke alarms alert occupants to the occurrence of a fire and contribute to both reduced fire spread through early identification and suppression as well as

195. Wermiel, The Fireproof Building.
196. National Housing Administration and National Research Council, "NBC 1941."
197. National Fire Protection Association, "Proceedings of the Twenty-Fifth Annual Meeting, 'Report of Committee on Building Construction.'"
198. Calder and Senez, "A Historical Perspective on Building Heights and Areas in the British Columbia Building Code."
199. Associate Committee on the National Building Code, "NBCC 1975."
200. Thomas, "The Use of Fire Statistics in Guiding Research and Code Development."

evacuation times. Occupant behaviour also plays a significant role in the fire safety of buildings; as smoking rates have fallen, so have fire deaths as a result of smoking, such that by 2009 mechanical/electrical failure has taken over as the single largest cause of residential fire outbreaks.[201] [202] It will be interesting to see how the continued decrease in smoking and the transition to induction cooktops impacts residential fire risk.

Firefighter practice has also come a long way from its crude beginnings of volunteer bucket brigades. By the early 1900s (when the foundations for the Code was being written), despite the fact that towns no longer relied on leather buckets and hand-pumped fire engines, they were still composed of highly combustible, exposed wood structures heated largely by wood stoves. Large cities relied on horse-drawn fire engines, rudimentary fire hydrant systems, and nascent firefighter training programs and tactics.[203] The formalization and mechanization (e.g. smoke alarms with automatic notification, water-fog techniques, and aerial ladders) of firefighting in combination has greatly increased their capacity to handle building fires,[204] yet the integration of firefighter perspectives and statistics to influence NBCC improvements remains severely underdeveloped.[205] [206] [207]

Canada and Noncombustibility

Immediately following the publication of the 1953 NBCC, work began on updating the height and area values for the following edition. One key development was the addition of two distinct approaches to updating the code; a short term one primarily concerned with updating limits and a long term one aimed at revisions to the holistic format of height and area limits.[208] Four key areas of risk relative to size were outlined by Ferguson: life hazard (primarily concerned with exiting), inaccessibility (for firefighters), control of fuel (limiting total fire load), and risk of collapse.[209]

This was a formative time for the Code, redefining the purpose and intent of the Code while simultaneously entrenching some of the underlying assumptions. One of these issues was defining *noncombustibility*, which until the 1960 NBCC has remained undescribed. Both the terms combustible and noncombustible had been used throughout the earlier versions of the Code but in defining the term, the application of its use also had to be reconsidered, *"the main committee recognize the limitations of defining non-combustibility by*

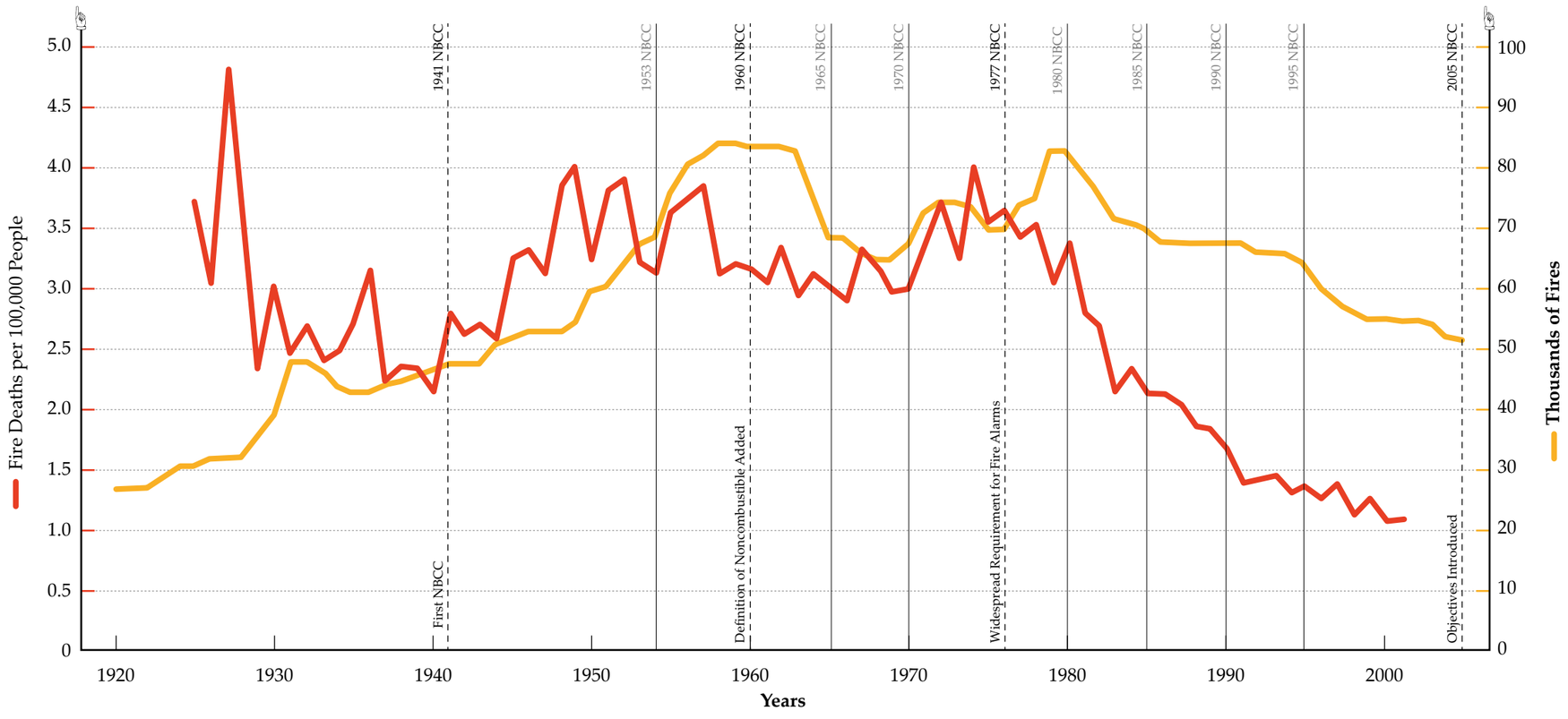
201. Canadian Centre for Justice Statistics, "Fire Statistics in Canada, 2005 to 2014."
202. Thomas, "The Use of Fire Statistics in Guiding Research and Code Development."
203. Donal M. Baird, The Story of Firefighting in Canada.
204. Angle et al., Firefighting Strategies and Tactics.
205. Donal M. Baird, The Story of Firefighting in Canada.
206. Elizabeth Weckman, Burning Up: Expert Interview #3.
207. Thomas, "The Use of Fire Statistics in Guiding Research and Code Development."
208. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."
209. Associate Committee on the National Building Code, "Minutes of the Sixth Meeting of the Panel on Heights and Areas (Advisory Fire Group)."

Year	1905	1914	1915	1930	1938	1941	1942	1965	2005 introduction of objective-based code	2020
Building Code	NBFU Model Code	NFPA Schedule	NBFU Model Code	NBSFR Elimination of Waste	City of Hamilton Municipal Code	NBCC	NBSFR Elimination of Waste	NBCC		NBCC
Types of Construction	Fireproof	Full Protection	Fireproof	Fully Protected	Fireproof	Fire Resistive	Fireproof	Noncombustible		Noncombustible
	Mill	Partial Protection	Hollow Block	Protected	Mill	Heavy Timber	Incombustible	Heavy Timber		EMTC
	Ordinary	Temporary Protection	Mill	Heavy Timber	Ordinary	Masonry and Frame	Exterior Protected	Wood		Heavy Timber
			Ordinary	Masonry and Frame	Metal Frame	Unprotected Metal	Wood Frame			Combustible
			Wood Frame	Unprotected Metal	Wood Frame	Wood Frame				
				Wood Frame						

f 2.21

Types of construction specified by building codes throughout time.

Although the table does not correspond exactly with the graph below, the number of construction categories does not seem to have a significant role in reducing fire deaths. Further, the current construction types bear significant semblance to those in 1905



f 2.22

Number of fire deaths per capita and total number of fires in Canada from 1920 to 2005.

Fire deaths and number of fires did not fall meaningfully after the introduction of noncombustible construciton as a core tenet of the code. These outcomes only began to fall after the introduction of fire alarms in the 1977 NBCC, suggesting that noncombustibility does not play a large role in the safety of occupants.

a simple furnace method as proposed, and study the application of such a test in relation to flame spread and fire resistance tests and the application of such a test for the Building Code."[210] Notably, the testing standard used to define noncombustibility is largely unchanged to this day (as explored further in Barrier #7).[211]

The combination of reassessing building size limits and construction types enabled the evaluation of building risk to be redefined through three core principles that continue in use today.[212] First, size as the hazard and construction as the mitigation measure; state the size, then establish the restrictions to make the size safe, allowing for the elimination of distinctions between construction classifications at the time (fire resistive, wood frame, etc.). Second, building size should be based on height, with area and subsequently construction type as a function of height. Third, the construction of the building should be sufficient to contain a fire on a single floor, such that area should be defined as the maximum permitted dimensions of a single floor. From these principals, Ferguson draws out a number of rules which provide a rational methodology to defining building size and construction relative to use such that the acceptable risk created by a variety of buildings might be the same (figure 2.23). The application of these rules was accepted as the long-term approach to reevaluating risk. Unfortunately, austerity measures introduced in 1962 grounded any efforts to enact this long-term vision.[213]

Little fundamental change occurred throughout the 1970s and 80s, although the limits to using *noncombustibility* as a core tenet of the Code was identified not long after its introduction, and the suggestion to move towards a performance-based approach was put forth.[214] Similarly, the identification of the role of tradition in building regulation and the role of the fire department were noted.[215] However, the limits of control continued to move towards smaller spaces and focused on fire safety issues like exiting and flame spread in conjunction with the gradual shift from property protection to life safety.

One noteworthy change during this period was the conversion of imperial units to metric units in the 1977 NBCC. This change highlights the imprecision with which the code approximates safety in favour of administrative ease, *"in converting the requirements for heights and areas of buildings, for example, one square meter was assumed to be equivalent to ten square feet. This greatly simplified the conversion of the many Tables of heights and areas in the Code and is considered sufficiently accurate for its purpose."*[216] Although the conversion of 10

210. Associate Committee on the National Building Code, "Minutes of the Twenty-Fourth Meeting of the Associate Committee on the National Building Code."

211. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."

212. Associate Committee on the National Building Code, "Minutes of the Seventh Meeting of the Panel on Heights and Areas (Advisory Fire Group)."

213. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada," 111-117.

214. Ferguson, "The Problem of 'Noncombustible.'"

215. Ferguson, "Building Regulations."

216. Associate Committee on the National Building Code, "Minutes of the Fifty-Ninth Meeting of the Associate Committee on the National Building Code."

Rule 1: Required Fire Resistance

- Except for very small buildings, all buildings must have fire resistive construction which varies in degree from low to high depending on the number of storeys:
- …

Rule 2: Limiting Areas

- The total limiting area of all buildings shall be 50,000 square feet assuming the fire load is low (i.e., 10 lbs.).
- The total limiting area should be reduced by half to 25,000 square feet for high fire load (i.e., 30 to 40 lbs.).
- The basic areas outlined in the previous two points apply to the entire building. The area per storey is equal to the basic area divided by the number of storeys.
- Where combustible construction is used, the basic area will be divided by 2.
- …
- Size must be determined based both on area and volume and amount of combustibles and the nature of the combustibles such that, the fire department could be expected to extinguish it without undue difficulty under normal conditions.
- Reliance on the fire department is basic to this approach. It is unrealistic to attempt to provide barriers between buildings which are adequate under all circumstances to withstand a complete burn-out without the aid of the fire department at all.

Rule 3: Special Case for no Fire Resistance

- …

Rule 4: Limitation on Combustible Construction - Fire resistance may be in combustible as well as non-combustible construction based on

- Area is further limited (See Rule 2).
- Combustible construction with no concealed spaces is permitted in buildings 5 storeys high except that joist floors are permitted to this height.
- Wood frame walls and partitions are permitted in buildings 3 storeys high.
- Restraints on combustible construction should be more related to height than area.

Rule 5: Exterior Wall Requirements

- All exterior walls are required to have fire resistance and be of non-combustible construction when buildings are more than 2 storeys.
- ...

Rule 6: Basic Fire Resistance Requirements

- ...

f 2.23

Fundamental rules to determine building areas and heights proposed by R.S. Ferguson, a precursor to a performance code that was never to come.

Excerpt from: Keith Calder and Peter Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada" (Sereca Consulting Inc, March 19, 2015).

sq. ft. to 1 m^2 is close, it is not accurate (10 sq. ft. is actually 9.29 m^2) and arbitrarily increases heights and areas by 7% (figure 2.20).

In 2005, the NBCC was revised to an objective-based format. The framework, which continues to be used in the 2020 NBCC, defines a number of high-level objectives and links regulations to them. Importantly, the objectives were derived from the existing historical requirements, rather than redeveloping regulations to match clearly stated objectives. The change, instead of enabling progressive and holistic fire safety research, aimed to clarify the goals of requirements and reduce complexity. Functional and intent statements were developed to link the purpose of the requirements to its associated objectives. However, due to the formulation of overarching objectives from existing regulations, those regulations formed the basis of safety, and therefore must be acceptable solutions. These regulations, which are largely prescriptive, form the aptly named "acceptable solutions" portion of the code (Division B) which acts as the risk against which any alternative solutions must be measured (figure 2.24).

The move to an objective-based format was a strong step forward, however it still limits the design of buildings to a strict bound. Performance-based codes, such as those enacted by Japan, England, Australia, New Zealand, and Sweden, are founded on the principle that all building designs are acceptable, provided they meet a quantifiable limit. The move towards a performance code is essential in order to reduce embodied carbon emissions. It will dispel many of the arbitrary decisions embedded within the Code, enable innovative design approaches, optimize fire safety measures, and incorporate societal decision making.[217] However, these performance limits are a long way from being developed; it is of critical importance that that current Code objectives reflect the value of embodied carbon and that NBCC regulations enable the construction of low embodied carbon housing.

f 2.24

Excerpts from NBCC 2020.

217. I. Oleszkiewicz, "The Concept and Practive of Performance-Based Building Regulations."

National Building Code of Canada 2020

The NBC sets out technical provisions for the design and construction of new buildings. It also applies to the alteration, change of use and demolition of existing buildings. The NBC establishes requirements to address the following five objectives:

- safety (OS)
- health (OH)
- accessibility (OA)
- fire and structural protection of buildings (OP)
- environment (OE)

Objectives

The objectives describe, in broad terms, the overall goals that the NBC's requirements are intended to achieve. They serve to define the boundaries of the subject areas the Code addresses. However, the Code does not address all the issues that might be considered to fall within those boundaries.

The objectives describe undesirable situations and their consequences, which the Code aims to prevent from occurring in buildings. The wording of most of the definitions of the objectives includes two key phrases: "limit the probability" and "unacceptable risk." The phrase "limit the probability" is used to acknowledge that the NBC cannot entirely prevent those undesirable situations from happening. The phrase "unacceptable risk" acknowledges that the NBC cannot eliminate all risk: the "acceptable risk" is the risk remaining once compliance with the Code has been achieved.

A-1.2.1.1.(1)(b) Code Compliance via Alternative Solutions.

Where a design differs from the acceptable solutions in Division B, then it should be treated as an "alternative solution." A proponent of an alternative solution must demonstrate that the alternative solution addresses the same issues as the applicable acceptable solutions in Division B and their attributed objectives and functional statements. However, because the objectives and functional statements are entirely qualitative, demonstrating compliance with them in isolation is not possible. Therefore, Clause 1.2.1.1.(1)(b) identifies the principle that Division B establishes the quantitative performance targets that alternative solutions must meet. In many cases, these targets are not defined very precisely by the acceptable solutions—certainly far less precisely than would be the case with a true performance code, which would have quantitative performance targets and prescribed methods of performance measurement for all aspects of building performance. Nevertheless, Clause 1.2.1.1.(1)(b) makes it clear that an effort must be made to demonstrate that an alternative solution will perform as well as a design that would satisfy the applicable acceptable solutions in Division B—not "well enough" but "as well as."

Part Three: Barriers to Low Embodied Carbon Housing

Interview with Keith Calder

PhD Candidate, M.Eng., P.Eng., Fire Protection Engineer

Can you talk a little bit about the direction you think the code is headed?

What are some of the hard barriers to the Code being responsive that you're coming up against?

Let's talk about history for a second. How was the Code developed? What were the key moments?

Those climate events that you're talking about, are you referring to the energy code and the introduction of encapsulated mass timber construction?

f 3.01

Excerpts from interview with Keith Calder on August 14, 2024.

See Appendix A for full transcript.

"There are a lot of initiatives going on to try and make the code more responsive to changes and especially environmental changes. But there's a lot of tradition wrapped up in the code that is holding it back, and that's a bit of a roadblock too. There's an intent [for the code] to become more responsive, but I don't really see a plan at this point in time to getting around that traditional base to the code. I think there's a lot of goodwill, but not a lot of reasonable solutions to get there."

"There are things that are considered to be fundamental parts of the code, and those are the things that are really difficult to change and to address. These are things like egress, you know, one versus two stairs is considered to be a fundamental part of the code. Combustibility-noncombustibility is another thing considered to be a fundamental part of the code. And when I say fundamental, those are the things that are very much linked to tradition and something that has been called the tried-and-true methods. These are methods that really have been demonstrated through experience and time and because of that, there's a hesitation to pull back on those because of that long history of what I would say is perceived performance - not necessarily quantifiable performance."

"There wasn't a whole lot that changed until you hit the 1990s, where there was a real push to incorporate sprinkling as a solution - or more holistic solution. Originally, [sprinklering] was intended to included in all Part 3 buildings, but they had to pull back on that a little bit because of a lack of water supply in certain jurisdictions in Canada. Despite this, they still were able to get sprinklering in many more buildings by way of the building code. So that was a key point, but they didn't revisit some of the earlier solutions to see whether or not sprinklers addressed those hazards and those earlier solutions could be pulled back on. One example of this is combustibility.

The next big milestone was the development of the objective-based codes which happened in the early 90s around the same time that sprinklers are being further incorporated into the code and that went right through until the 2005 National Building Code where the objective-based approach was published. We haven't had a whole lot go on since then, other than what we're seeing now, with a lot of significant climate issues coming up that need to be addressed or at least incorporated into the building code. I think we're at that next point where we need a substantial change in the building code in order to be more responsive to those to those events."

"We need to be able to support the other necessary changes in the building code. Because of the changes, because of the energy code, because of the changes to building envelope, the fire requirements are somewhat of an impediment to those changes in in some respects. With mass timber, because it's one of those fundamental [risk] parts of the code, we need to revisit that fundamental aspect to make sure that, from a risk perspective, that the earlier concern about how combustible stuff burns has been addressed. We need, from a fire regulatory perspective, we need to be more responsive to remove those barriers or readdress them earlier, things that were considered as risks earlier."

Meta-Barriers

Contemporary climate change is undoubtedly one of the largest challenges in the history of mankind. The slow, creeping buildup of emissions requires a concerted global effort to reverse course on an economy and society that relies on petrochemical consumption. Despite a widespread acknowledgement of the issue in Canadian architecture,[218] the adoption of low carbon design remains limited. In this chapter, seven regulatory barriers to low embodied carbon housing within Part 3 of the NBCC are described and analyzed. Changes to the Code to overcome these challenges are proposed with regard to fire regulation and newfound consideration for embodied carbon. There are, however, a number of systemic, overarching, and process-based barriers to low carbon design with regard to fire safety, largely stemming from conservatism; these barriers are also described and analyzed.

The Code is a barrier in itself; containing over 1500 pages, it has ballooned from its original 422-page document.[219] The complexity, the difficulty of discerning its intent, and the dense legalese in which it is written make the NBCC a formidable document to understand, let alone tangle with. Similarly, provincial differences in adoption and modification offer challenges to all aspects of the construction community while AHJs (and even the professionals within them) vary significantly in their involvement, interpretation, and enforcement of the Code. Importantly, education on both the specifics and generalities of fire safety is poor; practitioners often only have a meagre grasp of fire risk, fire engineering professional are rarely contracted before the design stage is complete, and many regulators are unable to adequately evaluate performance-based Alternative Solutions.[220] These shortcomings typically lead to last-minute inclusion of basic fire safety requirements and adherence to prescriptive Code requirements.

The NBCC is not straightforward; there is combustible and noncombustible construction (and heavy timber and encapsulated mass timber), each with innumerable exceptions to the use of materials within them.[221] The impediment that complexity and tradition create to the adoption of sustainable construction is well documented.[222] [223] [224] To put it bluntly, adapting to new processes is a hassle. Integrating and adopting practices which are different

218. Royal Architectural Institute of Canada, "RAIC Responds to the Government of Canada Regulatory Framework for an Oil and Gas Sector Greenhouse Gas Emissions Cap."

219. National Housing Administration and National Research Council, "NBC 1941."

220. Maluk, Woodrow, and Torero, "The Potential of Integrating Fire Safety in Modern Building Design."

221. Calder et al., "A New Tool to Design Above-Grade Walls for the National Building Code of Canada."

222. Hofman, de Vries, and van de Kaa, "Keeping Things as They Are."

223. Law and Beever, "Magic Numbers and Golden Rules."

224. Ferguson, "Building Regulations."

from business as usual introduces complexity, cost, and risk, which inhibits the percolation of necessary low carbon design. In an increasingly litigious industry, interpretation of the Code (which is necessary for both Acceptable and Alternative Solutions) tends towards conservatism in order to limit professional liability. Status quo bias and confirmation bias lead professionals away from emerging options to focus on the benefit of conventional practices whereby they highlight their success in the past, which may not be indicative of their usefulness in the future (see the "hot hand" theory in basketball).[225] These preconceptions create a significant gap between the perceived and real benefits of any change in custom. Similarly, and particularly relevant to this thesis, is that the more complex information is perceived to be, the greater it is avoided.[226]

In the context of the NBCC, regulations must deal with exceedingly complex dynamics applied to relatively unknown configurations and scenarios. It is simply easier to leave regulations the way they are than to invest the time, money, and effort required to unravel the intricacies and externalities of the Code. This barrier to advancement was evident in the abandonment of performance targets for the NBCC in the 1960s.[227] To say that conservatism is unreasonable, is, in itself, unreasonable. The consequences of fire are enormous, both to life, property, and culture.[228] These consequences have historically outweighed the costs of more onerous requirements, leading to increasingly rigorous regulations. As the carbon cost of fire safety regulations, and the cost of carbon,[229] becomes more evident, the Code must begin to contend with both meta- and technical barriers to limit its holistic implications.

225. Pelechrinis and Winston, "The Hot Hand in the Wild."

226. Hofman, de Vries, and van de Kaa, "Keeping Things as They Are."

227. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

228. Bobbette, "A Forensics of the Future."

229. Bressler, "The Mortality Cost of Carbon."

Interview with Shoshanna Saxe

Ph.D., M.Sc., P.Eng., Associate Professor (U of T),
Canada Research Chair in Sustainable Infrastructure

What direction of research are you looking at next?

Can you talk about the relationship between urban architectural form and embodied carbon?

Is there anything that you think is missing from this conversation? What future research is most pressing?

How does fire safety play into low carbon cities?

f 3.02

Excerpts from interview with Shoshanna Saxe on October 9, 2024.

See Appendix A for full transcript.

* The distance is 21 m: Phineas Harper, "Edwardian Morals, Thatcher and Bad Design – Why Britain's Homes Are so Hot," The Guardian, July 20, 2022, sec. Opinion.

"It's one thing to say "we want things to change, we want a sustainable society, we want an equitable society, we want better infrastructure," but it means something very different, practically, if we say we want a sustainable society in five years or we say we want a sustainable society in 100 years because the suite of tools and the speed of change [alter] really dramatically. We are very bad at talking about time as a profession and as a society. I think it's something we need to start thinking about and talking about more because there are temporal horizons to the things we want to achieve [which impacts] our toolkit, what we should be doing, and how long we can wait. The longer we wait, the smaller our toolkit gets."

"The really simple one is if you build single-family [homes], it'll be massively more embodied carbon than if you build any other form. From high-rise to mid-rise or even smaller 3-4 storey buildings, as soon as you move from building one unit per building to 3/4 units per building, you've made a huge impact in the sustainability credentials of our city, in terms of how many resources are needed to maintain the current population… The other ones are things like setbacks and lot coverage. It's a version on the same [issue], right? The more land you don't use in one spot, the more you [have to use] somewhere else, and the more infrastructure you need to serve it. If you put 10 units in 10 buildings, you get 100 units. You need the linear infrastructure, the road, the sidewalk, the sewers, and the electricity lines to connect those 10 buildings. If you put 100 units in one building, now you have much less road and much less water infrastructure per person…That built in fear of extreme density and poverty together from the 19th and early 20th century which is still evident in our laws and our decision making about cities [today]. My favorite weird building code fact [is that] in the UK the rule about how far apart two houses have to be through their backyards, and it's the distance [at which] two men wearing white shirts can no longer see each other's nipples.* "

"I think we don't talk enough about efficient use of resources. The conversation is too dominated by what technology or what magic material can we slot in that lets us do everything the way we're currently doing it, but fixes the problem… You can have a really sustainable wood building and you can have a really sustainable concrete building. Focusing on [the question of] "couldn't we just switch to wood?" misses the fact that you can just design concrete buildings really well…. Generally, people want totally different outcomes [than we currently have], but want to have all the inputs remain the same."

"The way in which I encounter fire safety is people using it as an excuse to design badly. And it's not just fire safety, it's all safety; we need really wide roads because our fire trucks are big. [Why don't we] get smaller fire trucks? We can't build more units because fire this or fire that. Fire is a very real way that people get hurt and we need to take fire safety seriously, but so are all the other things. [Building] roads that are too wide is a real thing that kills people too. Not having enough housing available is a real thing that leads to massive negative societal consequences. Increasing our consumption and pollution is a really bad thing. That's the way in which things like fire safety or other things that are like safety come up. We protect for certain kinds of well-being but not others."

Urban Scale Barriers

The GHG contribution of urban areas is estimated to account for between 40% and 80% of global emissions, depending on the bounds of estimation and whether a consumption- or production-based approach is taken.[230] [231] [232] [233] Buildings, and their consumption of energy, have long been an area of focus for emissions reductions given the size of their contribution and potential for minimization. While operational carbon emissions were being codified (and reduced) by the NBCC, municipal standards, and private certifications, the importance of urban embodied carbon has come to light.[234]

At the same time, there is increasing recognition that decisions made at the building scale can only be so impactful. While a single building may reach net-zero carbon (or any other metric), a smaller change to the underlying system may have much larger impacts as it scales to the neighbourhood or city level. Important benefits, efficiencies, and synergies that reach beyond the relatively fixed scope of "buildings" can be achieved when measures are carried out at an urban scale, particularly through addressing transportation GHG emissions.[235] The emissions enabled, and in some sense, required, by a particular development type might be considered within the embodied carbon of a project. Architecture is responsible for more than itself in isolation; it has a duty to address the world which creates it, and in turn, the lifestyles it enables.

Similarly, studying the urban scale allows the relationship *between* buildings to come into focus, highlighting the ways in which we codify spatial adjacencies and public space. It is unrealistic, though, to expect the NBCC to encompass all relationships to the building in question. The urban scale barriers however, reveal some of the unexpected knock-on effects of regulation. Making clear the assumptions around related issues, particularly the fire service, will ensure a consistent application and standard to evaluate building across AHJs with differing capabilities of intervention. Removing the onus from the AHJ authority will impact embodied carbon by ensuring consistent priorities are being applied across the country to ensure that large, system-wide value shifts are enacted. The top-down approach will also benefit the AHJs by eliminating their requirement to implement challenging and time-consuming change.

230. Dhakal, "GHG Emissions from Urbanization and Opportunities for Urban Carbon Mitigation."
231. Satterthwaite, "Cities' Contribution to Global Warming."
232. Luqman, Rayner, and Gurney, "On the Impact of Urbanisation on CO2 Emissions."
233. Jones and Kammen, "Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density."
234. Rankin and Saxe, "A Future Growth Model for Building More Housing and Infrastructure with Less Embodied Greenhouse Gas."
235. Rauland and Newman, "Why Cities?"

Urban scale embodied carbon benefits may be enabled by the removal of barriers, but will only be realized through the widescale adoption of the new proposed allowances. A single mixed-use building or single narrowed road will have little benefit, but the adoption of mixed-use buildings through an entire neighbourhood or a system of laneways, newly recognized as roads, will greatly impact the entirety of embodied carbon emissions. The barriers identified in this section are concerned with the rise of suburbia, the low-density development outside of urban cores. Significant literature exists which focusses on the various unintended consequences of this type of development ranging from financial burdens (individual and municipal)[236] to automobile dependence.[237] Authors have also highlighted how sprawl (whether you prefix it with urban, suburban, or exurban) has increased traffic fatalities,[238] obesity rates,[239] and notably to this thesis, GHG emissions[240] and severity of fire outcomes.[241] While each barrier focusses on the fire impacts specific to the issue at hand, there is a decreasing level of safety from fire as density decreases; firefighter response times increase by as much as 50%, fire incidents increase by 7%, property loss increases by 4%, and fire deaths by 3%.[242]

236. Fischel, "The Economic History of Zoning."
237. Mattioli et al., "The Political Economy of Car Dependence."
238. Yeo, Park, and Jang, "Effects of Urban Sprawl and Vehicle Miles Traveled on Traffic Fatalities."
239. Ewing et al., "Relationship between Urban Sprawl and Physical Activity, Obesity, and Morbidity – Update and Refinement."
240. Lotteau et al., "Critical Review of Life Cycle Assessment (LCA) for the Built Environment at the Neighborhood Scale."
241. Lambert, Srinivasan, and Katirai, "Ex-Urban Sprawl and Fire Response in the United States."
242. Lambert, Srinivasan, and Katirai.

Barrier #1:
Access Routes

Regulation and Interpretation

Road networks reflect the urban morphology of a city by recording historic periods and broad political choices. Often seen primarily for their ability to provide room for transportation and building access, their importance as social and cultural spaces is increasingly being recognized in North America. Though, all of these impacts are essential to consider, the provision of firefighter access is of utmost importance for the development of our cities and our assumed level of personal safety. The parameters of these access roads, their width and load capacity, are just one of the components of an integrated fire safety system, but have an outsized impact on the urban fabric of a city.

Subsection 3.2.5. Provisions for Firefighting in the NBCC (figure 3.03) provides the requirements for the location, design, and principles of access routes. Although 3.2.5.4.(1) notes that these requirements only apply to buildings greater than 3 *storeys* in height or 600 m^2 in *building area*, the provision for Part 9 buildings (9.10.20.3.), which is assumed to govern the buildings that fall outside these limits, is exceedingly vague and refers back to the note associated with 3.2.5.4. The wording of the Part 9 provision, "Access for fire department equipment shall be provided to each *building* by means of a *street*, private roadway or yard. (See Notes A-9.10.20.3(1) and A-3.2.5.6.(1).)", creates a significant grey area which provides little regulatory oversight and often means that the AHJ will default to the overriding requirements for Part 3.[243]

Although the requirements for Part 3 access routes seem straightforward, one of the key lines states that the access routes shall "have a clear width not less than 6m unless it can be shown that lesser widths are satisfactory". Despite all parts of the NBCC being subject to Alternative Solutions, this clause makes explicit that lesser widths can be satisfactory but places the burden of proof upon the applicant. Note A-3 and A-3.2.5.6.(1) delegate the authority of firefighting means to the local AHJ fire department, "Firefighting capability can vary from municipality to municipality. Generally,

f 3.03

Excerpts from NBCC 2020.

243. Canadian Commission on Building and Fire Codes, "NBCC 2020," 9-80 Division B.

3.2.5.4. Access Routes

1) A *building* which is more than 3 *storeys* in *building height* or more than 600 m^2 in *building area* shall be provided with access routes for fire department vehicles

a) to the *building* face having a principal entrance, and

b) to each *building* face having access openings for firefighting as required by Articles 3.2.5.1. and 3.2.5.2. (See Note A-3.2.5.4.(1).)

3.2.5.5. Location of Access Routes

1) Access routes required by Article 3.2.5.4. shall be located so that the principal entrance and every access opening required by Articles 3.2.5.1. and 3.2.5.2. are located not less than 3 m and not more than 15 m from the closest portion of the access route required for fire department use, measured horizontally from the face of the *building*.

2)…

3.2.5.6. Access Route Design

1) A portion of a roadway or yard provided as a required access route for fire department use shall

a) have a clear width not less than 6 m, unless it can be shown that lesser widths are satisfactory,

b) have a centre-line radius not less than 12 m,

c) have an overhead clearance not less than 5 m,

d) have a change of gradient not more than 1 in 12.5 over a minimum distance of 15 m,

e) be designed to support the expected loads imposed by firefighting equipment and be surfaced with concrete, asphalt or other material designed to permit accessibility under all climatic conditions,

f) have turnaround facilities for any dead-end portion of the access route more than 90 m long, and

g) be connected with a public thoroughfare. (See Note A-3.2.5.6.(1).)

2)…

A-3.2.5.6.(1) Fire Department Access Route

The design and construction of fire department access routes involves the consideration of many variables, some of which are specified in the requirements in the Code. All these variables should be considered in relation to the type and size of fire department vehicles available in the municipality or area where the building will be constructed. It is appropriate, therefore, that the local fire department be consulted prior to the design and construction of access routes.

larger municipalities have greater firefighting capability than smaller ones… Although it is reasonable to consider that some level of municipal firefighting capability was assumed in developing the fire safety provisions in Part 3, this was not done on a consistent or defined basis. The requirements in the Code, while developed in the light of commonly prevailing municipal fire protection levels, do not attempt to relate the size of building to the level of municipal protection. The responsibility for controlling the maximum size of building to be permitted in a municipality in relation to local firefighting capability rests with the municipality."[244]

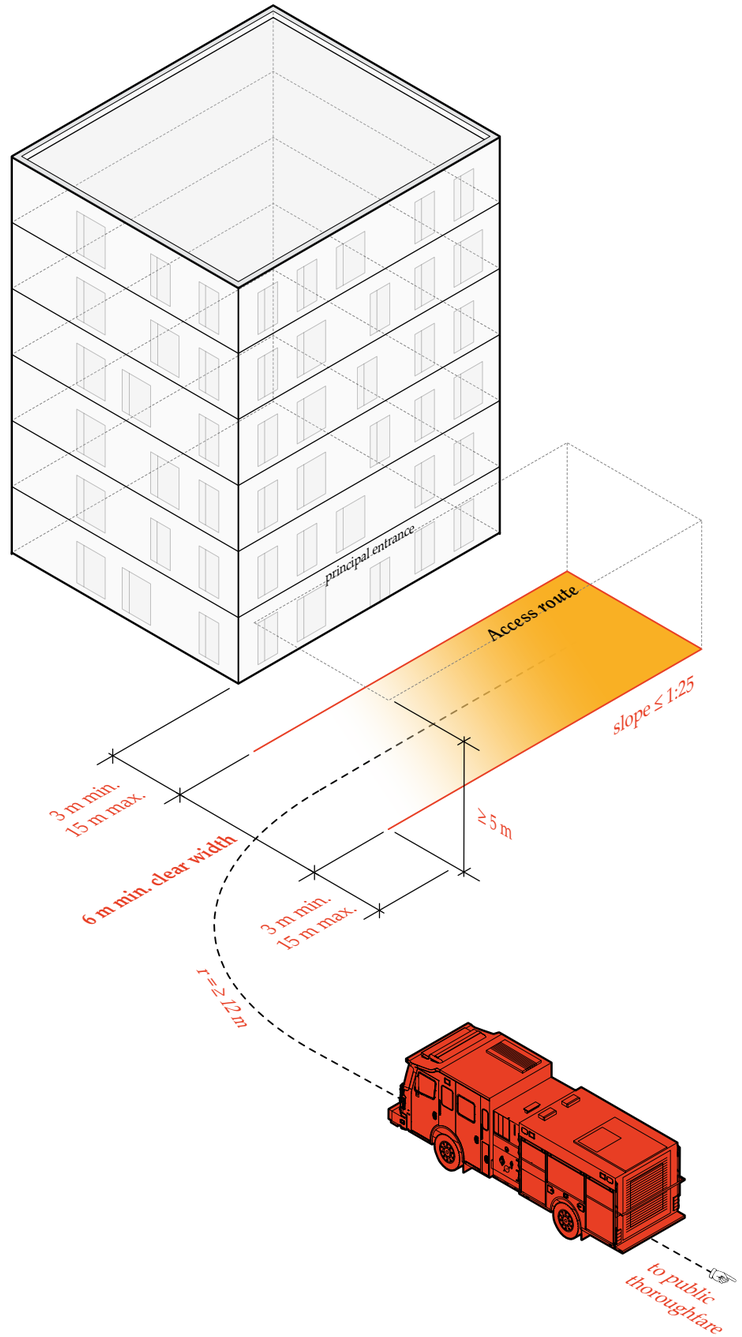
While allowing the local AHJ fire department to have the final say over access route widths makes sense, Sentence 3.2.5.5.(1) is antithetical to the purpose of a national model code; it does not provide a high level of consistency across jurisdictions. The note associated with section 3.2.5.6. further highlights this abdication of regulation to the local level and more specifically, to the type of fire department vehicles. The extrapolation of this note, and the manner in which it is written, make the minimum street width a function of the firetruck size – rather than the other way around. Taking the distances stated in Sentences 3.2.5.5.(1) and 3.2.5.6.(1)(a), the minimum clear width of a street must be 6 m, bounded by 3 m on either side (assuming there are buildings on both sides of the street), for a total building-to-building distance of 12 m (39') minimum (figure 3.04).

Ideal street widths vary significantly depending on who is asked and the context. The implication of this regulation, however, is that only a certain type of urbanism can be built in Canada. Rome, for example, regularly has widths of less than 3 m between building faces, while Copenhagen sits around 8 m, Aukland at about 12 m, and the West End neighbourhood of Vancouver at 25 m.[245] The density that street width creates has large impacts on both urban form, occupant lifestyles, and embodied carbon. Despite its inclusion in the code, rarely is the NBCC the governing document regarding minimum width; most municipalities have planning documents that detail unique widths. Toronto, for instance, outlines a minimum width of 3.3 m for a one-way road and 6.6 m for two lanes – of further interest, the design guide notes that a minimum laneway width of 2.7 m may be considered under special circumstances.[246] While the NBCC is rarely referenced in street design, it provides the legal underpinning from which municipalities derive their widths (in combination with a variety of other factors) and fire departments, their response capability.

244. Canadian Commission on Building and Fire Codes, 3-225 Division B.

245. "Google Maps Satellite View."

246. Transportation Services, City of Toronto, "Lane Width Guidelines."



f 3.04

Minimum dimensions for an access route.

These requirements form the basis for all new streets in Canada and represent a significant relationship between buildings and urban form.

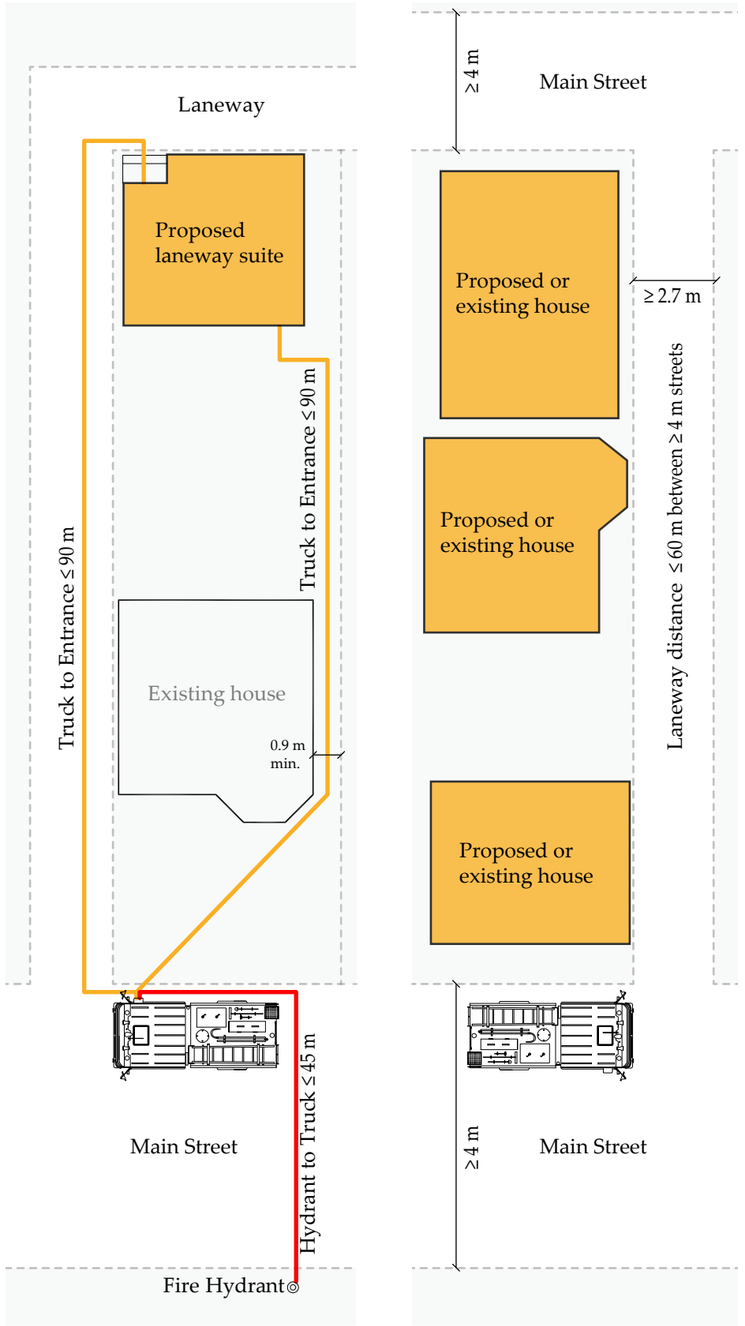
Another significant implication of these regulations is the restriction to laneway suites and accessory dwelling units in urban areas. As the Code is written, the access requirements for these buildings excludes the laneway itself, requiring only an *access route* through the property to comply. To simplify and clarify the requirements, the City of Toronto released a document outlining how they can comply with the Ontario Building Code requirements for fire department access (figure 3.05). [247] The report increases the maximum travel distance from the *access route* to the *laneway suite* or *accessory dwelling unit* from 15 m as specified in the NBCC, to 45 m (without additional measures) or 90 m (through the provision of either: automatic sprinkler and exterior strobe or, increased fire protection materials and exterior strobe). Similarly, it decreases the path of travel dimensional requirements to "a minimum of 0.9 metres wide by 2.1 metres high" from the assumed path of travel requirements that equal the *access route* requirement of 6.0 metres wide by 5.0 meters tall in the NBCC. The changes enable the fire truck to be parked on the street and firefighters to travel (and run hose) through the side yard or laneway in order to access the accessory building. These significantly altered requirements suggest that the regulations in the NBCC are more onerous than necessary (although neither are based on quantifiable data), and that Code provisions which provide fire access methodology tailored by building type could be applied at a broader scale.

Fire Safety Impact

Emergency responders (firefighters, EMS, and police, among others) are responsible for enacting the governmental responsibility of safety and risk management of its people. The general requirements of the AHJ are enabled by the establishment of infrastructure (e.g. roads, fire hydrants) and public service buildings (e.g. fire stations, hospitals). As a result, the policies, both general and specific, of the AHJ are determined in large part by the competencies and abilities of its first responders. An example of this approach can be seen throughout the history of building regulations in the limiting of building heights to the distance that firefighters could spray water from the street.[248] Streets and access roads are another example of this – the provisions outlined in the NBCC provide the context in which the fire department (of an assumed capability) can do their job.

247. City of Toronto, "PH16.10 - Laneway Suites: Fire Access Requirements."

248. Calder and Senez, "A Historical Perspective on Building Heights and Areas in the British Columbia Building Code."



a) City of Toronto Laneway Suites

b) Japan Roji

f 3.05

Alternative methods of firefighter access for laneways in Toronto and Japan.

Although these tactics hail from drastically different geographies, they employ similar strategies - right down to requiring an exterior strobe in some cases.

There is little information regarding how the 6 m minimum access road was derived. One answer might be found in the 1915 NFBU model code, in which height and area limitations were derived as a factor of street width, a byproduct of the space required for the firefighting approach of spraying water from the road.[249] The area limits were based on an average street width of 60 ft (18 m) but could not be less than 20 ft (6 m). Another, perhaps more reasonable, answer is that standard vehicles must not be more than 2.6 m in width, which allows two vehicles to pass one another.[250]

In either case, little information was found to correlate fire safety and street width. A multi-step literature search was conducted in May 2024 to find relevant publications regarding the fire safety impact of street width. Although there has been significant research around road width with regard to road safety,[251] walkability,[252] [253] and speed control,[254] [255] there is little research regarding the impact of road width on firefighting capabilities. The literature reviewed focuses on route optimization and network analysis while no research was found to focus on the impact of road width to firefighting capability once the engine has arrived on scene. [256] [257]

The time between an emergency call and firefighter arrival at the scene is a critical factor in the determination of fire severity impacts, with fire spread increasing significantly at a response time of greater than four minutes (though fatalities show little correlation, likely as a result of self-evacuation before the fire service arrives).[258] [259] Traffic has a significant impact on fire response time in urban areas and is often incorporated into traditional emergency navigation systems.[260] One study found that when navigation systems incorporate real-time traffic, weather conditions, and road widths, response times could be reduced by up to 17%.[261] The results suggest that road width may have an impact on response time through the reduction or addition of traffic time, but further research is needed. Studies tend to focus on road width as the variable, and accept fire vehicle width as constant.[262] [263] Though this may be the socially accepted approach, the width of a fire department vehicle can vary greatly (figure 3.06).

A Rapid Intervention Vehicle (RIV) is a type of emergency vehicle commonly used in Europe and some parts of Asia. They typically use a pickup truck or cargo van as their chassis and are fitted out with a reduced set of equipment compared to other firefighting vehicles. Evidence shows that these vehicles reduce average response time by 37.2 seconds plus 2.5 seconds per km compared to traditional fire

249. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada," 56.

250. Highway Traffic Act.

251. Schramm and Rakotonirainy, "The Effect of Road Lane Width on Cyclist Safety in Urban Areas."

252. Guzman, Arellana, and Castro, "Desirable Streets for Pedestrians."

253. Fonseca et al., "Built Environment Attributes and Their Influence on Walkability."

254. Mecheri, Rosey, and Lobjois, "The Effects of Lane Width, Shoulder Width, and Road Cross-Sectional Reallocation on Drivers' Behavioral Adaptations."

255. Lewis-Evans and Charlton, "Explicit and Implicit Processes in Behavioural Adaptation to Road Width."

256. Zainal et al., "Fire Vehicle Route, Response Time, and Service Coverage Optimizations in Pekojan Urban Village, Tambora Subdistrict Fire Hotspot of Jakarta City Indonesia."

257. Ozcan-tatar et al., "Routing and Navigation Solutions for Emergency Vehicles in Urban Emergency Management."

258. Buffington and Ezekoye, "Statistical Analysis of Fire Department Response Times and Effects on Fire Outcomes in the United States."

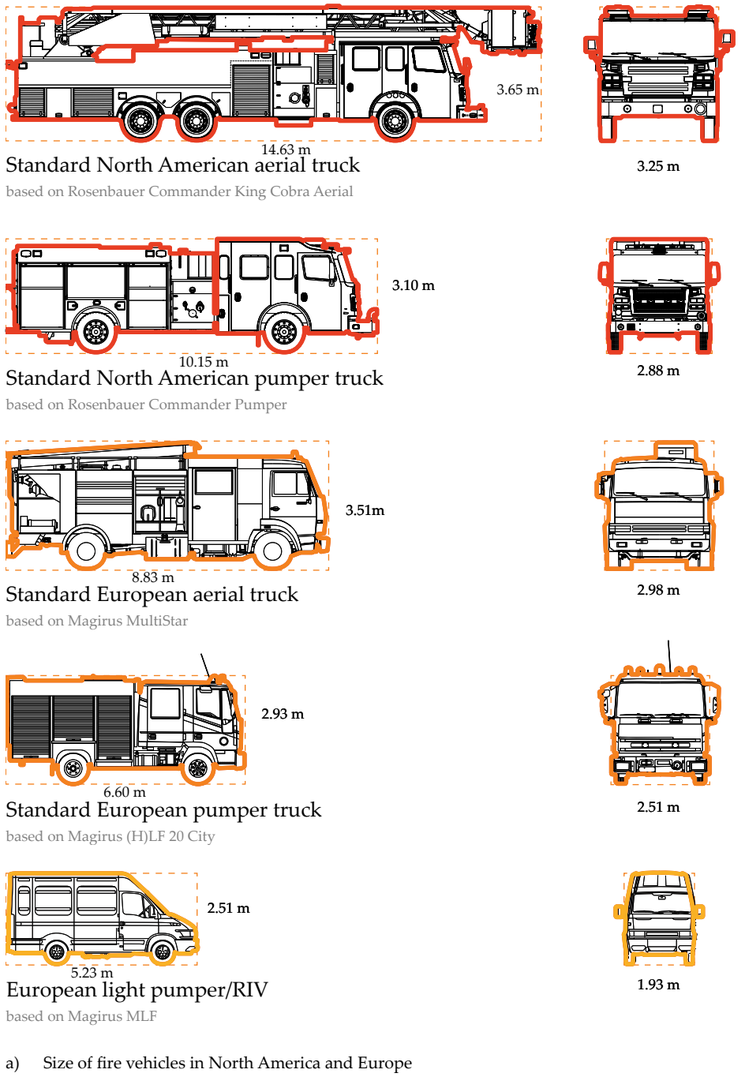
259. Challands, "The Relationships Between Fire Service Response Time and Fire Outcomes."

260. Shaaban et al., "A Strategy for Emergency Vehicle Preemption and Route Selection."

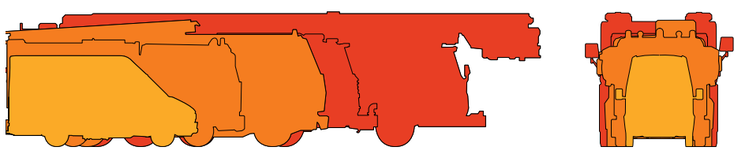
261. Ozcan-tatar et al., "Routing and Navigation Solutions for Emergency Vehicles in Urban Emergency Management."

262. Lee, Kim, and Lee, "Firefighting in Vulnerable Areas Based on the Connection between Fire Hydrants and Fire Brigade."

263. Zainal et al., "Fire Vehicle Route, Response Time, and Service Coverage Optimizations in Pekojan Urban Village, Tambora Subdistrict Fire Hotspot of Jakarta City Indonesia."



a) Size of fire vehicles in North America and Europe

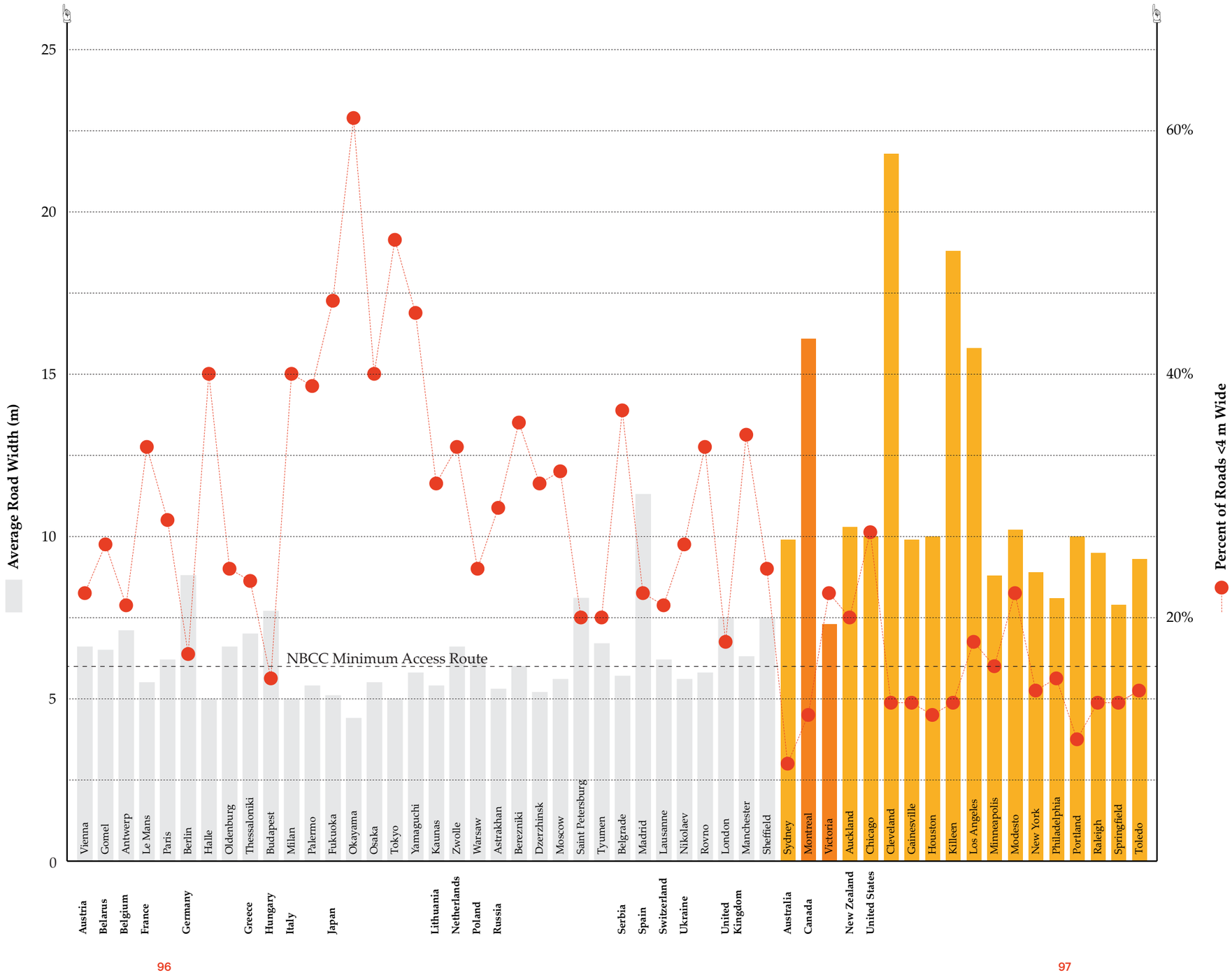


b) Visual comparison of fire vehicle sizes

f 3.06

Comparison of fire vehicle sizes in North America and Europe.

European vehicles typically separate distinct functions and tools into different vehicles which allows for smaller and lighter trucks. An important advantage of the European vehicles is that as the wheel base of vehicles get shorter, the turning radius also decreases, allowing for access to tighter spaces.



f 3.07

Road width by country between 1987 and 2014.

Note that these values are average road widths, including multi-lane roads and highways. Minimum road widths required for emergency access are likely more narrow than presented values. Although the age of cities in Europe tends to be used as an argument for their narrow roads, the range presented represents broadly contemporary development. Only data from Europe, Japan, and Commonwealth countries was selected from the source dataset due to relatively similar regulatory systems. Australia, Canada, New Zealand, and the United States are grouped together as they are all land rich countries. There is a clear relationship between the average width and the percentage of roads less than 4 meters.

engines.[264] Further, in urban conditions, the fixed reduction increases to 120 seconds, and evidence suggests that sending the RIV ahead of the rest of the crew could further reduce these times. A back of the envelope calculation implies that these time savings, scaled across all Canadian fire departments would save 6 lives per year (reduction of 3.7%).[265] [266] Smaller emergency vehicles may also have the beneficial impact of reducing both pedestrian and responder safety.[267]

Similarly, the firefighting approach assumed in the NBCC, in which the firetruck parks in front of, or immediately adjacent to the building with the fire event, is not the only option. In Japan, the Building Standards Law (BSL) is the binding regulation for buildings and cities. In 2004, the BSL was revised to preserve Roji (lanes in Japanese), which are roadway between 2.70 - 3.99 m wide. This update was in response to a 1950 rule which changed the minimum road width from 2.7 meters to 4 meters in order "to improve sanitation and cleanliness in the area, and to ensure sufficient room for fire engines to pass, as well as to impede the spreading of fires."[268] While Roji may be worse performing than wider roads in the event of disaster response (particularly in earthquakes), the beneficial impacts of these narrow lanes on the urban fabric were determined to outweigh their safety risk. Overall, road networks have a larger impact on firefighting ability than the minimum widths of lane ways. While fire engine access is important, it is not essential that every lot fronts onto a road wide enough for a fire truck. Instead, a tiered access method was shown to be effective. In order to comply with the BSL, the lanes must end in dead-ends and by less than 60 m in length between roads that are equal or greater than 4 m in width. This approach allows fire engines to park on the 4 m road and extend hoses to the source of the fire (figure 3.05). This approach takes in the multi-faceted aspect of firefighting and maximizes the consideration of hose length. Further, the practice of exterior firefighting has shifted towards a reliance on sprinklering and interior access. This change is reflected in the removal of street facing requirements and allowances.[269] While it is still vital that firefighters are able to reach the building with adequate water supply, access routes should no longer require the space for aerial fire equipment in most cases.

Narrow street widths are not just confined to Japan. The minimum road width for the UK is 3.7 m, though this requirement was clarified to mean, "a 3.7 m carriageway (kerb to kerb) is required for operating space at the scene of a fire. Simply to reach a fire, the access route could be reduced to 2.75 m over short distances."[270] While legal minimum road widths for other countries were not

264. Guldvik, Helseth, and Grimsby, "Rapid Intervention Vehicles' Impact on Fire Departments' Response Time."

265. Henrik Jaldell, "How Important Is the Time Factor? Saving Lives Using Fire and Rescue Services," *Fire Technology* 53, no. 2 (March 1, 2017): 695–708, https://doi.org/10.1007/s10694-016-0592-4. The study estimates that 0.00035 lives could be saved every turnout if response times were reduced by 1 minute.

266. Canadian Centre for Justice Statistics, "Fire Statistics in Canada, Selected Observations from the National Fire Information Database 2005 to 2014" (Canadian Association of Fire Chiefs, September 2017). Approximately 173 Canadians die by fire each year in 20,533 building fires; 20,533*0.00035*53/60 seconds = 6.3 lives/year.

267. Hsiao, Chang, and Simeonov, "Preventing Emergency Vehicle Crashes."

268. Usui and Asami, "An Evaluation of Road Network Patterns Based on the Criteria for Fire-Fighting."

269. GHL Consultants Ltd, "Technical and Process Risks in 5 and 6 Storey Wood-Frame Buildings of Residential Occupancy."

270. Department for Transport and Ministry of Housing, Communities, and Local Government, "Manual for Streets."

found, they may be assumed based on a study of average road widths built between 1987 and 2014.[271] These numbers include multi-lane roads and highways that are wider than building code minimum so it can be assumed that the actual minimum road widths are significantly smaller (figure 3.07). 50% of the European and Japanese cities presented have *average* road widths narrower than the NBCC minimum access route which suggests that fire safe urban developments are possible with significantly reduced road widths.

Embodied Carbon Impact

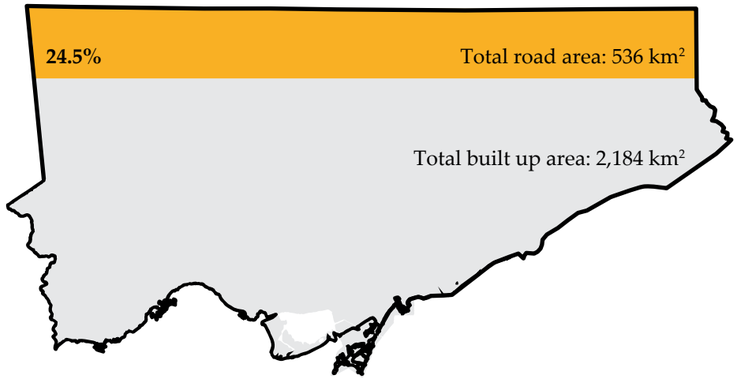
It is difficult to calculate the embodied carbon impact of access road widths as there are both direct and indirect costs. Direct embodied carbon reductions come from decreased road paving, which although small, is not an insignificant amount of a project's total embodied carbon. Indirect embodied carbon reductions are multiple and varied, from reducing sprawl, increasing blue and green infrastructure, reducing urban heat island effect, and encouraging active transportation. For the purposes of this study, the reduction in road paving and sprawl is considered.

At both a country and city scale, Canada has an outstandingly large percentage of land use dedicated to roads; approximately 25% of the build-up area of the GTA is roadway (figure 3.08).[272] Despite its enormous coverage, the carbon impact of road and right-of-way (ROW) widths are rarely considered since they are outside of the scope of a typical development project and fall into the management of the AHJ. This thesis finds that the embodied carbon of a roadway can vary significantly based on aggregate sourcing and its replacement cycle (dependent on the number and weight of vehicles),[273] but typically fall in the 70 $kgCO_2/m^2$ range (figure 3.09). Paving emissions can easily account for up to 9% of a missing middle project's embodied carbon; designing to the NBCC minimum would account for approximately 4.5%, while a reduced width could reduce this value to only 2.3% (figure 3.10). These numbers become even more significant as the density of a lot decreases. For a low-rise detached or semi-detached house, the minimum access road width can reach 12% of the total project embodied carbon (assuming 30 m^2 of roadway at 79 $kgCO_2e/m^2$ and 30-year lifespan; 200 m^2 house at 200 $kgCO_2/m^2$ and 60-year lifespan). At the scale of GTA, roads account for approximately 90.3 $MtCO_2e$ of embodied emissions.

271. Lamson-Hall and Angel, "The State of the Streets."

272. Statistics Canada, "The Changing Landscape of Canadian Metropolitan Areas."

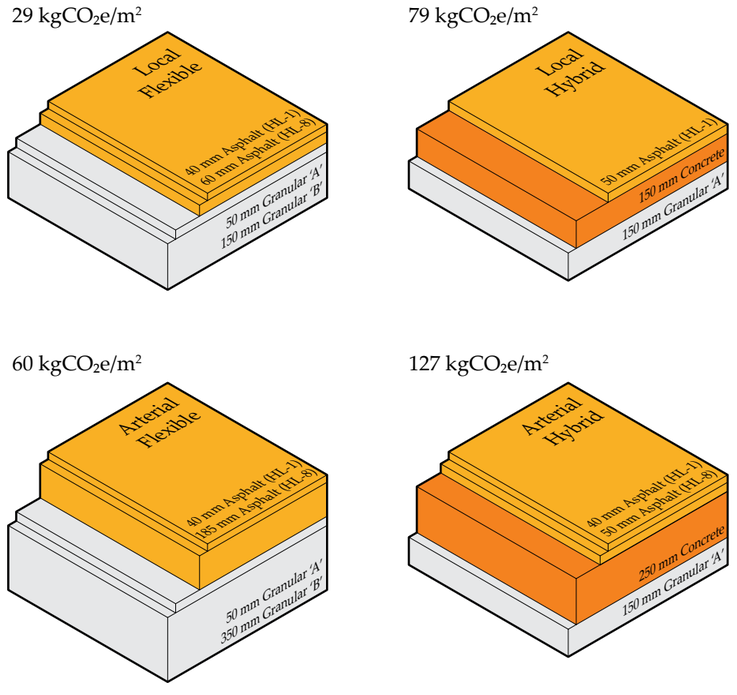
273. City of Toronto, Applied Research Associates Inc., "Structural Pavement Design Guidelines."



f 3.08

Total road area in the City of Toronto.

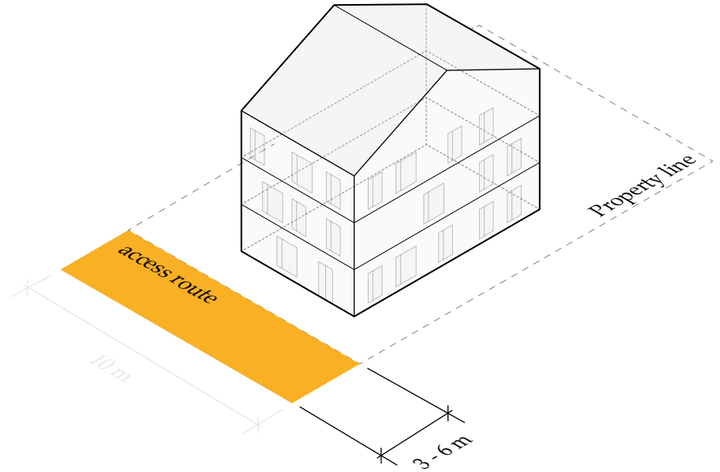
The road coverage in Toronto has an embodied carbon of 59.0 MtCO2e. Vancouver, Montreal, and Calgary, have 27.7, 48.7, and 27.8 MtCO2e respectively.



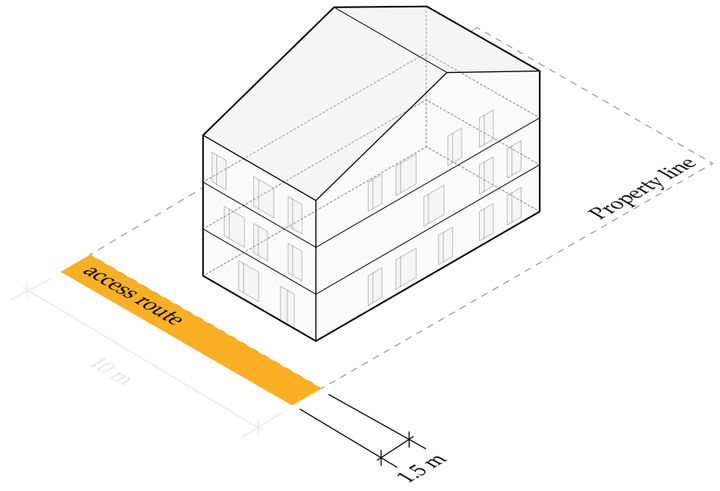
f 3.09

Embodied carbon of roadway paving used in Canada.

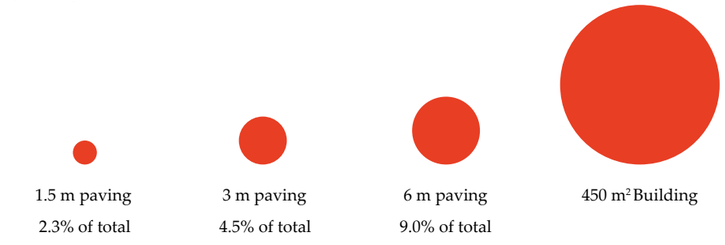
Local road designs account for 2500 annual average daily traffic (AADT) while the arterial designs account for 75,000 AADT. The City of Toronto uses a predominantly hybrid approach to road paving.



a) Minimum and typical access route width



b) Proposed minimum access route width



c) Embodied carbon of paving and building

f 3.10

Comparison of current and proposed access route width relative to the embodied carbon of a building.

The drawing assumes a building of 450 m2 with an embodied carbon intensity of 375 kgCO2e/m2 and a lifespan of 60 years. Paving emissions use values for the arterial hybrid and a typical lifespan of 30 years.

Accounting for the embodied carbon emissions of urban sprawl relative to dense urban centers is complex and has not been widely studied, although efforts are underway. Similarly, there is the challenge of decoupling the standard practice of conflating lot coverage and building height into a single moniker of "density". Isolating and analyzing the impact of each of these factors on the whole life carbon of an urban environment is required to estimate the impact of sprawl, rather than low-rise housing that typically accompanies it. By decoupling height and density, one study analyses four scenarios; high density, high-rise (HDHR), low density, high-rise (LDHR), high density, mid-rise (HDMR), and low density, mid-rise (LDMR).[274] High density refers to land coverage >40.2% while low density references <30.1%, high-rise refers to buildings 35-82 m tall (approximately 12-27 storeys) while mid-rise refers to buildings 11-35 m tall (approximately 4-12 storeys). For reference, Toronto yellow-belt neighbourhoods adjacent to downtown fall into the 40% coverage range and have less than 4 storeys.

The research finds that HDMR requires about 50% less land than LDMR to accommodate the same population which in turn lowers the life cycle carbon (through reduced infrastructure costs) and demand for land. It also finds that taller buildings have a significant impact on life cycle carbon when the urban population is kept constant (for example, housing 20k people in low-rise buildings is more efficient than 20k in high-rise).[275] It is also important to note that while this study includes the life cycle carbon associated with land use change, it does not include the relative infrastructural or green space impact of high or low density.

In a fixed land area scenario, which more accurately represents the situation faced in urban centers across Canada, the per capita emissions of HDMR are far lower than any other option; 0.19 $MtCO_2e$ compared to 0.34, 0.35, and 0.43 for LDMR, LDHR, and HDHR respectively. Further, the total carbon emissions difference between the LDMR and HDMR is relatively small. The results show a correlation between height and life cycle carbon, but show an inverse relationship between increasing density and life cycle carbon across all scenarios. The study dispels the belief that building height is the best option to accommodate increasing population from a carbon perspective. Further, and notable to this thesis, it is worth considering that this study does not consider the effect that height or density have on the carbon associated with allowable material selection.

274. Pomponi et al., "Decoupling Density from Tallness in Analysing the Life Cycle Greenhouse Gas Emissions of Cities."

275. Pomponi et al.

Proposed Change

There are two parts to fire access: driving to the fire scene and fighting the fire. The "6 m clear width" wording assumes the same width is required for both of these activities – when it is unlikely that this is necessary.[276] In order to appropriately regulate these activities, further definition is necessary. Does the "clear width" of 6 m refer to a curb-to-curb width? If so, does that width include parked cars (if not, many one-way streets would be in violation of this requirement), and similarly, is it assumed that the drive lanes of a roadway are "clear" in the event of a fire?

In the driving scenario, 6 m allows for two lanes of 3 m, with the assumption that vehicles travelling either direction pull to the side to let the fire vehicle by, though the clearance for this to occur is not possible in a 6 m width. The Highway Traffic Act (HTA) limits the maximum vehicle width to 2.6m without a special permit, while most compact cars sit around 1.75m, full size SUVs and pickup trucks tend to be about 2.1 m in width.[277] Given this, with both cars pulled to the side, it leaves just over 2 m for the fire truck to pass – which is too narrow for typical fire department vehicles.[278] Once the truck is at the scene of the fire, the 6 m width is presumably to allow for outriggers to extend on aerial trucks (typically 5.5 m in total width). These outriggers are used to stabilize the vehicle while the bucket is extended, however this vehicle is rarely used on buildings below 6 storeys. Further, some aerial trucks have outriggers that extend beyond 6 m in order to access greater heights, such as Torontos newly acquired aerial that can reach up to 70 m.[279]

As design and best practice guides focus more intently on how to best divide up the street (e.g. how much space to allocate for cars, stormwater runoff, bikes) in recognition of the value of this space beyond motor vehicle movement, the conversation tends to focus on divvying up the right-of-way. Rarely does the discourse extend to the systemic view of how much land should be devoted to streets at all – with the trade-offs implicit with different uses ignored completely. Tying minimum road width to the occupancy and size of buildings (as has been done in the past)[280] would have the benefit of providing a consistent level of safety to the spectrum of building sizes, without creating overly onerous restrictions, all while reducing the dependency on local fire departments to set unique limits. One benefit of this would be the enablement of greater use of laneways. It is evident through their inclusion in the Toronto zoning bylaw, that fire-safe accessory dwelling units

276. Department for Transport and Ministry of Housing, Communities, and Local Government, "Manual for Streets."

277. Highway Traffic Act.

278. Pierce Manufacturing Inc., "Aerials."

279. Vaccaro, "Toronto's Bronto Skylift 230-Foot Aerial."

280. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada," 43-44.

and laneway suites are deemed to be possible without significant change. While municipal fire departments will still have the option of restricting minimum widths, the Code change will put the onus on fire departments to accommodate the Code rather than the other way around. Article 3.2.5.6. and the associated note have allowed the size of current fire department vehicles to dictate the limits of vast urban configurations. It is the tail wagging the dog whereby a $1 million emergency vehicle limits low embodied carbon, housing availability, billions in real estate value, and beyond that, the lives and culture that this type of housing creates. The following Code change is proposed (figure 3.11):

3.2.5.5. Location of Access Routes - removed

3.2.5.6. Access Route Design

1. A portion of a roadway or yard provided as a required access route for fire department use shall

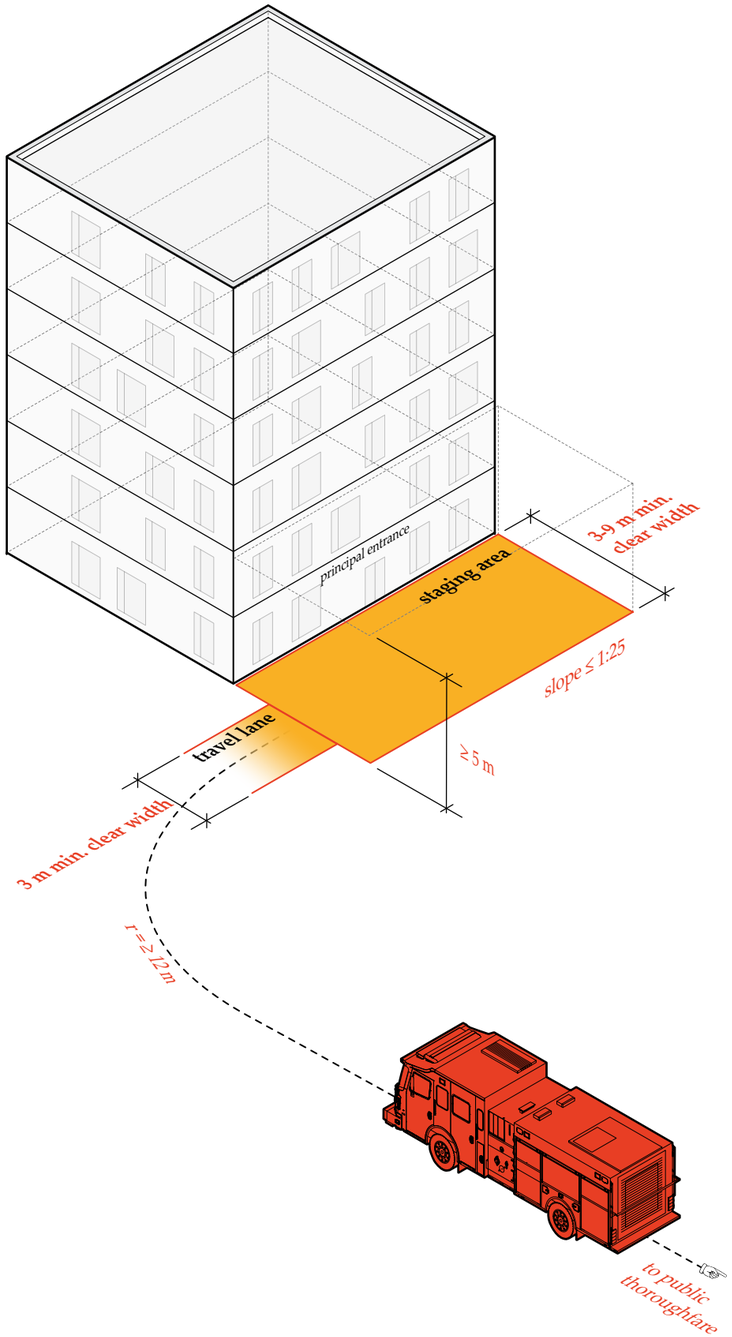
    a. have an unobstructed travel lane to the *building* with a clear width not less than 3 m,

    b. have an unobstructed staging area located so that, as measured perpendicularly from the face of the *building* to the closest portion of the access route, the principal entrance and every access opening required by Articles 3.2.5.1. and 3.2.5.2. are located not more than 15 m with a clear width not less than

        i. 3 m for *buildings* not more than 3 *storeys* in *building height*,

        ii. 6 m for *buildings* not more than 6 *storeys* in *building height*, or

        iii. 9 m for *buildings* greater than 6 *storeys* in *building height*



f 3.11

Proposed minimum dimensions for an access route.

The proposed requirements simplify access requiremets and clarify the difference between necessary width of a travel lane and the width required for staging. Further research and consultation is required to determine appropriate staging width and length limits.

Barrier #2: Zoning

Regulation and Interpretation

Most literature cites late 19th and early 20th century German land-use regulations as the precedent for North American style zoning, but the roots of Canadian development restrictions predate these rules by nearly 100 years. These zoning laws largely determine the urban form of a city which has a well documented impact on carbon emissions, both embodied and operational.[282] [283] Although current land-use regulation may not have any clear connection to fire control, early bylaws aimed at ensuring health, increasing real estate values, and perhaps most importantly, fire safety, formed the legal and technical basis for contemporary zoning.[284] [285] The split of these bylaws into distinct zoning and building code documents was not an entirely clean break, and as a result, the responsibility for urban fire safety is unclear and lingers in both documents (figure 3.12), to the detriment of embodied carbon.

The term *zoning* is typically understood as a stand-in for *comprehensive zoning* or *exclusionary zoning*, which is the subdivision of the entirety of land under an AHJ into different land-use categories. These zones carry different allowable occupancies and building typologies, typically manifesting in maximum densities, heights, and setbacks. At a high level, zoning is intended to align land-use at a municipal or regional scale to implement an urban plan; the vision of the city. However, in practice, zoning tends to be used as an instrument of financial and real-estate regulation at a per site scale.[286] [287] This expression, though unfortunate, is not unexpected given that the roots of zoning largely buoy on the "economic, social, and moral value of the single-family house by setting aside areas for its exclusive occupation".[288] These goals were implemented through the guise of fire safety.

The domain of development regulation came within the purview of municipalities (in Upper Canada) as a result of the 1792 Act to Guard Against Accidents by Fire in this Province.[289] This act was followed two years later by another which regulated the establishment of liquor sales, paving the way for municipalities to govern land

f 3.12
Excerpts from NBCC 2020.

282. Yu, Wiedmann, and Langdon, "Assessing the Greenhouse Gas Mitigation Potential of Urban Precincts with Hybrid Life Cycle Assessment."
283. VandeWeghe and Kennedy, "A Spatial Analysis of Residential Greenhouse Gas Emissions in the Toronto Census Metropolitan Area."
284. "A Brief History of Zoning Bylaws in Toronto."
285. Fischler, "Development Controls in Toronto in the Nineteenth Century."
286. Fischel, "The Economic History of Zoning."
287. Dehring and Lind, "Residential Land-Use Controls and Land Values."
288. Fischler, "Development Controls in Toronto in the Nineteenth Century."
289. 32 George III, An Act to Guard Against Accidents by Fire in This Province.

A-3 Application of Part 3; Firefighting Assumptions

Firefighting capability can vary from municipality to municipality... The level of municipal fire protection considered to be adequate will normally depend on both the size of the municipality (i.e., the number of buildings to be protected) and the size of buildings within that municipality...

Although it is reasonable to consider that some level of municipal firefighting capability was assumed in developing the fire safety provisions in Part 3, this was not done on a consistent or defined basis. The requirements in the Code, while developed in the light of commonly prevailing municipal fire protection levels, do not attempt to relate the size of building to the level of municipal protection. The responsibility for controlling the maximum size of building to be permitted in a municipality in relation to local firefighting capability rests with the municipality. If a proposed building is too large, either in terms of floor area or building height, to receive reasonable protection from the municipal fire department, fire protection requirements in addition to those prescribed in this Code, may be necessary to compensate for this deficiency. Automatic sprinkler protection may be one option to be considered.

Alternatively, the municipality may, in light of its firefighting capability, elect to introduce zoning restrictions to ensure that the maximum building size is related to available municipal fire protection facilities. This is, by necessity, a somewhat arbitrary decision and should be made in consultation with the local firefighting service, who should have an appreciation of their capability to fight fires.

The requirements of Subsection 3.2.3. are intended to prevent fire spread from thermal radiation assuming there is adequate firefighting available. It has been found that periods of from 10 to 30 minutes usually elapse between the outbreak of fire in a building that is not protected with an automatic sprinkler system and the attainment of high radiation levels. During this period, the specified spatial separations should prove adequate to inhibit ignition of an exposed building face or the interior of an adjacent building by radiation. Subsequently, however, reduction of the fire intensity by firefighting and the protective wetting of the exposed building face will often be necessary as supplementary measures to inhibit fire spread.

A-3.2.5.7.(1) Water Supply

The intent of Sentence 3.2.5.7.(1) is that an adequate water supply for firefighting be readily available and of sufficient volume and pressure to enable emergency response personnel to control fire growth so as to enable the safe evacuation of occupants and the conduct of search and rescue operations, prevent the fire from spreading to adjacent buildings, and provide a limited measure of property protection…However, where municipal water supply capacities are limited, it may be necessary for buildings to have supplemental water supplies on site or readily available.

uses which may have negative impacts (real or perceived) on their contexts. As is the case in common law, the details of an individual ruling are rarely of great importance, instead it is the purpose behind them which may be used as precedent for future cases, that is of paramount importance.[290] In 1834, the statute which turned the Town of York into the City of Toronto expanded its power to control broad planning decisions, an authority much needed in order to guard against the regularity of epidemics and conflagrations at the time.[291] The watershed regulation was a fire safety bylaw passed 11 years later which controlled both the location of industries that presented significant fire risk and the construction of firewalls between all buildings.[292] The bylaw contains within it all of the key characteristics of zoning: the identification of uses, a differentiation of areas, and spatial rules per lot.[293] Interestingly, it also stipulates requirements that are common in the building code: acceptable materials, opening sizes, and size limitations. These rules were further refined following the 1849 fire to directly relate building types to fire risk and a defined geographic "fire limits" within which all buildings had to be noncombustible construction; the lowest risk category was defined as single family buildings on large lots and were thus excluded from noncombustibility requirements. By 1870, Toronto had adopted a bylaw which consolidated land-use and construction controls into a single document which enabled the prohibition of any "nuisance", however that may be defined: "Municipal codes on building and land use are extensions of the police power, that is, the power of the state to constrain private activities and organize public action to preserve the health, safety, and welfare of the population."[294]

Modern regulations emerged around the turn of the century as informal practices were formalized. One notable example is the mechanization of land-use change, where streets could petition to be added to the fire limits, typically used to protect their houses from apartment buildings, "increasingly perceived as injurious to health and safety and especially to good order and morals".[295] Further, as economic and racial classes of people developed distinct building typologies, regulation followed – distinguishing an apartment from a dwelling (the former is a building which is occupied by more than two families). By 1912, in addition to any mercantile use deemed to be noxious, apartments could be forbidden in the name of morals, health, and fire safety.[296] The culmination of these regulations meant that by 1920, 32 years before the first official zoning bylaw, significant portions of Toronto were already enshrouded in regulations which distinguished residential use from all others *and* houses from

290. Stein, "The Municipal Power to Zone in Canada and the United States."

291. 4 William IV, An Act to extend the Limits of the Town of York; to erect the same Town into a City; and to Incorporate it under the name of the City of Toronto.

292. City of Toronto, An Act to Restrain the Erection of Furnaces and Manufactories Dangerous from Fires, to Regulate the Erection of Party Walls, and for Other Purposes Mentioned Therein.

293. Fischler, "Development Controls in Toronto in the Nineteenth Century."

294. Fischler.

295. Fischler.

296. City of Toronto, A Bylaw to Prohibit the Erection of Apartment or Tenement Houses, and of Garages to Be Used for Hire or Gain, on Certain Streets.

"If we put it to a vote in any one of your cities, I think we would find it very difficult to get a vote against an apartment house. I am not for it - don't misunderstand me - but I do recognize that it provides a very convenient way of living, and because of the servant question, which Mr. Davis alludes to, a great many people prefer it. Personally, I think it indicates a very bad tendency and will have a very bad effect on American life and upon our political and social conditions. I don't think you can have proper homes in an apartment house of the highest type.

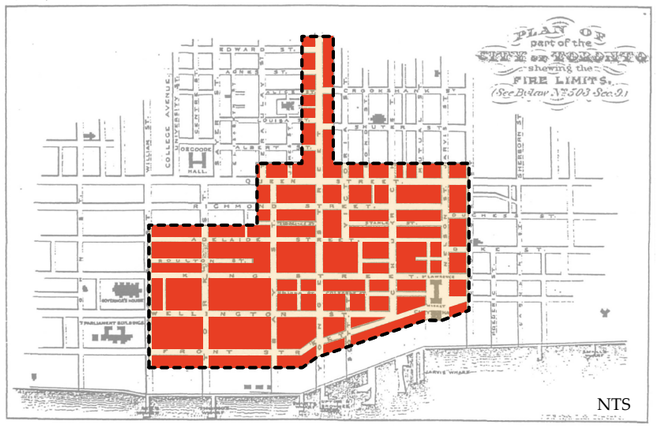
The question is, "How are we going to stop it?" I think there is a way; at least, I have tried it and I think it is going to work. In framing our laws to regulate the construction of dwellings of all kinds, do everything possible in our laws to encourage the construction of private dwellings even two-family dwellings, because the two-family house is next least objectionable type, and penalize so far as we can in our statute, the multiple dwelling of any kind, whether it is flat, apartment house or tenement house.

It is upon that theory that our new housing law in New York State was drafted. And the easiest and quickest way to penalize the apartment house is not through requiring larger open spaces, because I think that would be unconstitutional, but through the fireproofing requirements. If we require multiple dwellings to be fireproof, and thus increase the cost of construction; if we require stairs to be fireproofed, even where there are only three families; if we require fire-escapes and a host of other things, all dealing with fire protection, we are on safe grounds, because that can be justified as a legitimate exercise of police power. We can show the necessity of these extra precautions where many families live in a dwelling, and at the same time we have made it difficult too build apartment houses. I recommend that method to the conference. In our laws, let most of the fire provisions relate solely to multiple dwellings, and allow our private houses and two-family houses to be built with no fire protection whatever."

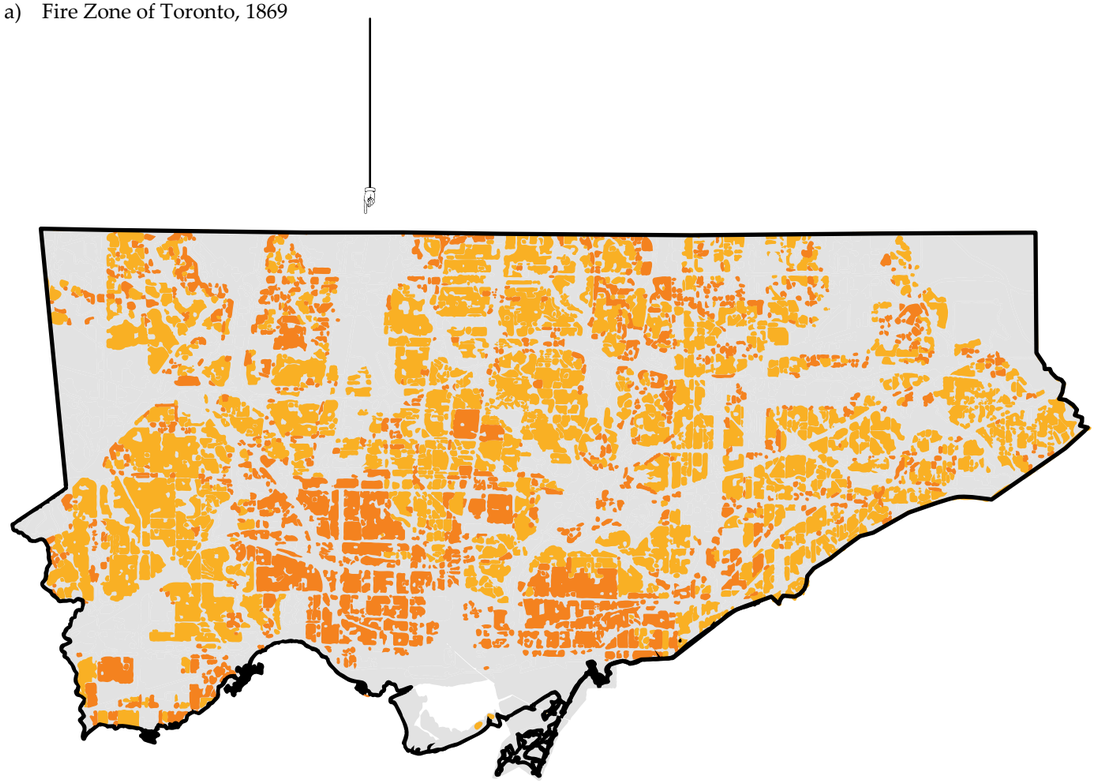
- Lawrence Veiller, 1913

f 3.13

Quote from Lawrence Veiller, "NHA Proceedings," 1913.



a) Fire Zone of Toronto, 1869

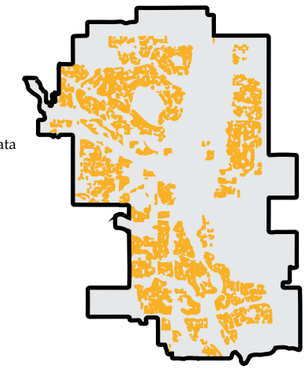


b) City of Toronto Zoning Map

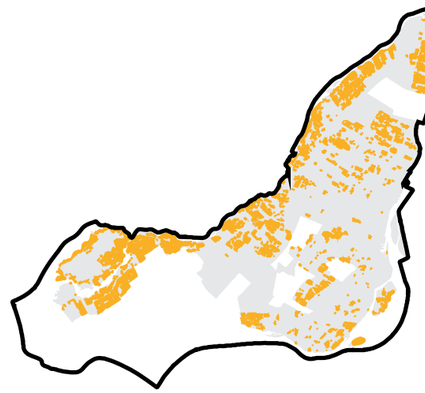
Fire Zone Blocks

Multi-unit Residential Zoning
Calgary, Montreal, and Vancouver maps omit this data

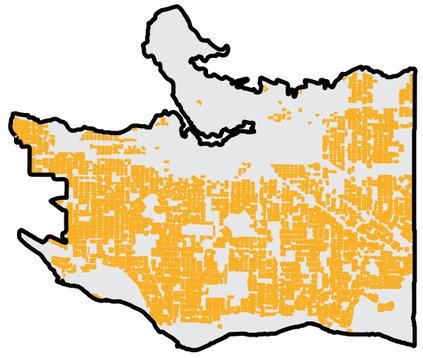
Detached Single Family Zoning



c) City of Calgary Zoning Map



d) City of Montreal Zoning Map



e) City of Vancouver Zoning Map

f 3.14

The evolution of Fire Zones to contemporary zoning.

Although the evolution between the two is not direct, the Fire Zones formed the lineage which would eventually lead to exclusionary zoning. Detached single family housing now dominates urban landscapes in Canada as a result of zoning decisions. Grey areas refer to all other zones and roadways.

apartments (or other multi-unit types). As the 20th century continued, the building code became the legal regulatory document regarding fire risk but zoning continued to discriminate against certain uses under the guise of fire safety in order to make them more expensive (figure 3.13).[297]

Though most of what has been described relates to Toronto, the development of land-use regulations was similar in most mid-size and large Canadian cities.[298] The low-embodied carbon barrier is twofold; first, zoning documents across the country which exclude the construction of most building types except detached homes, consequently encourage sprawl and restrict housing supply (Toronto's "yellow-belt" is perhaps the best example of this) (figure 3.14). Recent zoning reform efforts, such as the Ontario Bill 23 More Homes Built Faster Act and Toronto's multiplex bylaw, aim to enable incremental densification of existing single family home neighbourhoods, such that reconsidering the basis of these rules is timely. Second, the loosely defined bounds of the NBCC do not provide adequate description of assumed fire safety and thus likely over-estimate the need for higher carbon, fire-resistive measures.

Fire Safety Impact

Fire safety bylaws which tied together location, use, and material construction in a single document were instrumental in the development of our cities. They protected the urban fabric as a whole by separating lower risk uses from higher ones (foundries, tanneries, laundries,[299] etc.) and establishing minimum distances from neighbouring buildings. They also increased the fire safety of individual buildings by largely requiring noncombustible materials in a time where the alternative - combustible construction - meant exposed wood framing and wood siding in homes that used open flame for heating, cooking, and lighting. These laws created order in cities with rapidly developing industry and booming populations. However, in the decoupling (or perhaps de-throupling) of land use regulation and material construction requirements (and city planning), both documents developed independently despite their intertwined roots. The result is zoning documents that retain land-use categorizations and setback requirements defined by fire even though it has no legal role in the protection against conflagrations, and building codes that take on the role of building fire safety without appropriately extending consideration to the context in

297. Dennis, "'Zoning' before Zoning."

298. Dennis.

299. Luis Flores, "Zoning as a Labor Market Regulation," Theory and Society 53, no. 2 (April 1, 2024): 357–94, https://doi.org/10.1007/s11186-023-09539-y. Though laundries were higher risk than some other uses, their exclusion illustrates the racial and economic manner in which zoning was wielded to relegate typically poor, Chinese immigrants outside of desirable neighbourhoods, regardless of the real fire risk presented.

which the building (and its fire risk) exists.

The underlying issue in these overlaps, is that the bounds of their individual control is murky; it is not clear who, or what document, governs the issue of urban fire safety. While there are valid, non-fire, reasons for the distinction and separation of land-uses (noise, smell, pollutants, aesthetics), the derivation of these classes is not within the scope of this thesis. Instead, this section seeks to dispel the belief that there is any basis in fire safety through the prescription of *specific* land-uses. The inclusion of setbacks and coverage in an 1889 bylaw, two iconic parts of contemporary zoning regulations, was based on the British Metropolitan Building Act (also a key document in the development of the NBCC, see Part Two), explicitly making the relationship of a building to its surrounding context an object of public regulation in the name of fire risk.[300] These limits were based on experience rather than science,[301] while others were entirely fabricated in order to support the "good morals" of exclusionary zoning.[302] [303] However, once the bylaws separated into building code and zoning, setbacks became a largely self-referential aesthetic consideration – significant portions of the city were already built with setbacks that accounted for fire risk, so in order to fit in, future buildings must be built to the same standard (regardless of its now baseless roots).

Little contemporary research was found that correlated land-use and fire risk as a result of occupancy, which makes it difficult to analyze whether land use has any impact on urban fire safety. The National Fire Information Database published a report which outlines the number of fires by occupancy, but without the number of total buildings of each occupancy, it is impossible to compare these numbers.[304] The deficiency in late 20th and early 21st century conflagrations suggests that some combination of building code (including its requirements for smoke detectors, sprinklers, fire resistance ratings, etc.) and zoning is responsible for our increased safety. Given that the NBCC (in conjunction with the National Fire Code of Canada) governs all aspects of fire safety in buildings, it is likely that zoning does not significantly contribute to reduced contemporary conflagration risk. This is not to say, however, that zoning has no impact on fire safety as a whole. There is significant research regarding the wildland urban interface (WUI) in Canada. As a land-rich, sprawl-oriented country, built-up area is expanding such that wildfire risk is no longer a strictly rural phenomenon.[305] As forest fires intensify with climate change and urban (largely exurban) areas continue to grow, the WUI will play an increasingly

300. Fischler, "Development Controls in Toronto in the Nineteenth Century."

301. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada."

302. Baar, "The Anti-Apartment Movement in the U.S. and the Role of Land Use Regulations in Creating Housing Segregation."

303. Selma Siew Li Bidlingmaier, "Gentrification through Housing: Urban Eugenics and Lawrence Veiller's 1900 Tenement House Exhibition," Amerikastudien / American Studies 64, no. 2 (2019): 265–90. Housing reformers of the late 19th and early 20th century may have significantly bettered living conditions for many, however there are overt racist and classist underpinnings to this movement.

304. Canadian Centre for Justice Statistics, "Fire Statistics in Canada, 2005 to 2014."

305. Erni et al., "Developing a Two-Level Fire Regime Zonation System for Canada."

important role in mitigating the potential for conflagration.[306] [307] The NRC has published a comprehensive guide aimed at minimizing risks around the WUI, however it is up to the AHJ to codify and enforce these suggestions.[308]

The NBCC on the other hand, assumes that all fire (and fire risk) originates within the subject building and aims to control it through the division of the building into one or more fire compartments. This evolution over time, from containment at a neighbourhood block to an individual building to fire compartment, and increasingly, to the room of origin, has understandably generated opacity with which the Code extends its bounds beyond the buildings it governs. This unclear application is the result of its birth out of the separation of a single (or multiple) set of bylaws which governed fire safety. In addition to the fire originating within the building, the code assumes two other major relationships with its context: that adjacent buildings are the same size, configuration and location, and that firefighters will have limited involvement (although they must be able to access the site, see Barrier #1) (figure 3.12).[309]

The spatial separation limits are one example of how the Code contends with its context (figure 3.15). Spatial separation and limiting distances are intended to protect adjacent buildings from a fire originating within the subject building, often acting as a code-based "setback". These limits assume that the surrounding properties have buildings of the same size, area of openings, and distance to the property line which is rarely the case in real life. Accordingly, they have been the focus of ongoing research to determine their basis, legitimacy, and how they might be improved.[310] [311] [312] Some researchers suggest using heat release rate (HRR) as a performance metric which can be used to account for building contexts (see Barrier #7).[313] Further clarifying the role of firefighting in the protection of neighbouring buildings will also improve the legitimacy of these regulations; Note A-3 (figure 3.12) explains that the spatial separation requirements assume that firefighters do not arrive until 30 minutes after the fire starts, which may be excessively conservative.[314] Additionally, the determination of these limiting distance requirements was based on values from the relatively under-measured St Lawrence Burns test in 1957, with the sprinklered allowances determined without scientific reasoning.[315] Similarly, the Code often offers sprinklering as an appropriate mitigatory solution for a wide range of risks under the assumption that adequate water supply is available. This may not be the case during drought conditions, during simultaneous fires (typical of

306. Muffly and Birchall, "Key Elements of Defensible Space Land Use Bylaw Provisions in Wildland-Urban Interface Municipalities of Alberta, Canada."

307. McGee, "Completion of Recommended WUI Fire Mitigation Measures within Urban Households in Edmonton, Canada."

308. Canada, "National Guide for Wildland-Urban-Interface Fires."

309. Canadian Commission on Building and Fire Codes, "NBCC 2020," 3-225;226 Division B.

310. Yuan, "Challenges Faced in Application of Fire and Life Safety Design in Current Canadian Building Code."

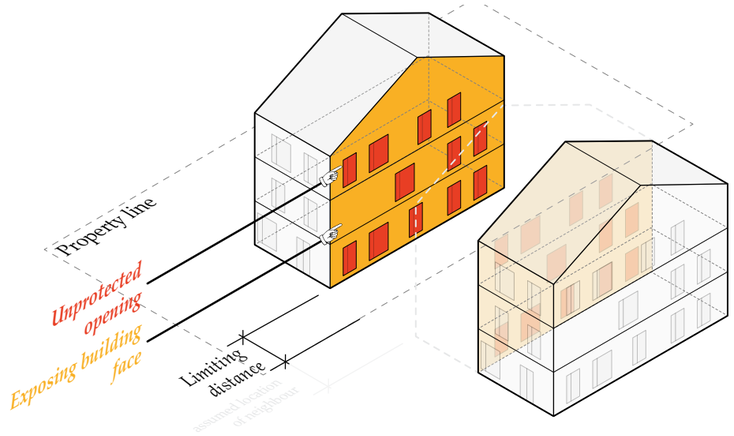
311. McGuire, "Fire and the Spatial Separation of Buildings."

312. Van Coile and Maeso, "Methodology for Evaluating the Safety Level of Current Accepted Design Solutions for Limiting Fire Spread Between Buildings."

313. Vytenis Babrauskas, "Engineering Variables to Replace the Concept of 'Noncombustibility,'" Fire Technology 53, no. 1 (January 1, 2017): 353–73, https://doi.org/10.1007/s10694-016-0570-x.

314. Matthew Pegg, "Toronto Fire Services Response Metrics."

315. Yuan, "Challenges Faced in Application of Fire and Life Safety Design in Current Canadian Building Code," 47-54.



a) Unprotected openings, limiting distance, and exposing building face

Exposing Building Face	Area of *Unprotected Opening* for Groups A, B, C, D and F, Division 3 *Occupancies*, %											
Max. Area, m²	*Limiting Distance*, m											
	0	1.2	1.5	2.0	2.5	3	4	5	6	7	8	9
10	0	16	24	42	66	100						
15	0	16	20	34	50	74	100					
20	0	16	20	30	42	60	100					
25	0	16	18	26	38	52	90	100				
30	0	14	18	24	34	46	78	100				
40	0	14	16	22	30	40	64	96	100			
50	0	14	16	20	28	36	56	82	100			
60	0	14	16	20	26	32	50	72	98	100		
80	0	14	16	18	22	28	42	58	80	100		
100	0	14	16	18	22	26	36	50	68	88	100	
150 or more	0	14	14	16	20	22	30	40	52	66	82	100

b) Table 3.2.3.1.-D Unprotected Opening Limits for a Building or Fire Compartment that is Sprinklered Throughout

Occupancy Classification of *Building* or *Fire Compartment*	Maximum Area of *Unprotected Openings* Permitted, % of *Exposing Building Face* Area	Minimum Required *Fire-Resistance Rating*	Type of Construction Required	Type of Cladding Required
Group A, B, C, D, or Group F, Division 3	0 to 10	1 h	*Noncombustible*	*Noncombustible*
	> 10 to 25	1 h	*Combustible*, *Encapsulated mass timber*, or *Noncombustible*	*Noncombustible*
	> 25 to 50	45 min	*Combustible*, *Encapsulated mass timber*, or *Noncombustible*	*Noncombustible*
	> 50 to < 100	45 min	*Combustible*, *Encapsulated mass timber*, or *Noncombustible*	*Combustible* or *Noncombustible*(1)(2)

c) Table 3.2.3.7. Minimum Construction Requirements for Exposing Building Faces

f 3.15

The concept of spatial separation with accompanying tables from NBCC 2020.

The type of construction (see Barrier #5) and type of cladding (see Barrier #7) required both have significant impacts on the embodied carbon of a building and rely on large assumptions as outlined in text. Table values highlighted in grey indicate combustible construction permitted; table values highlighted in yellow indicate combustible cladding permitted. Combustible cladding is tightly limited, requiring large setbacks from property lines. Significantly more restrictive limits are in place for unsprinklered buildings.

forest fire spread), or in rural areas where no fire hydrants exist. By omitting the assumed relationships, the AHJs are left to determine what volume of reserve water and flow rate are acceptable (figure 3.12).[316] [317]

Embodied Carbon Impact

As is the case with most large-scale problems, quantifying the embodied carbon impact of the zoning and NBCC barriers laid out in the first two sections is difficult to do. Zoning decisions, as the extension of municipal plans, lay out the direction for urban development through density, land coverage, infrastructure, and transportation, all of which have embodied carbon costs.[318] [319] [320] While zoning restrictions are not solely responsible for urban GHG emissions, there is a significant correlation between land-use and per capita emissions, particularly well studied in regards to operational carbon and transportation,[321] and more poorly understood in terms of embodied carbon (largely relying on the quantification of building types rather than urban form).[322] NBCC regulations with a relationship to zoning are similarly poorly understood, although their embodied carbon impact has not yet been quantified. The assumed impact will be assessed through possible material substitutions but proposed changes will have formal implications on embodied carbon as well.

Considering the relative newness of LCA and importance of embodied carbon, it is unsurprising that the field of urban scale LCA is still developing. In a comprehensive literature review, Seyedabadi and Eicker, identified 150 papers which tackled this topic, although only 9% analyzed the whole urban scale and further, only one paper analyzed the whole urban scale for embodied, operational and transportation related emissions. [323] A number of difficulties were identified which restrict this type of analysis including uncertainty introduced by using building archetypes and significant time required for a building-by-building approach. [324] [325]

The study by Yu et al. that completed a comprehensive urban LCA focusses on a suburban neighbourhood in Australia, which presents similar urban form and electricity emissions to a Canadian context.[326] [327] It found that embodied, operational and transport emissions make up 28%, 32%, and 40% of the 50-year life-cycle emissions, respectively.[328] These percentages are similar to those found by another study which used a literature review of non-holistic studies

316. Jim Sephton, Canadian Risk Services Ltd., "Water Supplies for Suburban and Rural Fire Fighting."

317. Opta Information Intelligence Corp., "Water Supply for Public Fire Protection: A Guide to Recommended Practice in Canada."

318. Pomponi et al., "Decoupling Density from Tallness in Analysing the Life Cycle Greenhouse Gas Emissions of Cities."

319. Zizzo, Kyriazis, and Goodland, "Embodied Carbon International Policy Review."

320. Zuluaga, Karney, and Saxe, "The Concept of Value in Sustainable Infrastructure Systems."

321. VandeWeghe and Kennedy, "A Spatial Analysis of Residential Greenhouse Gas Emissions in the Toronto Census Metropolitan Area."

322. Rankin et al., "Embodied GHG of Missing Middle."

323. Seyedabadi and Eicker, "A Critical Review of Urban Scale Life Cycle Assessment of the Built Environment."

324. Seyedabadi and Eicker.

325. Mirabella, Allacker, and Sala, "Current Trends and Limitations of Life Cycle Assessment Applied to the Urban Scale."

326. "Australian National Greenhouse Accounts Factors."

327. Environment and Climate Change Canada, "Emission Factors and Reference Values: Version 2.0."

328. Yu, Wiedmann, and Langdon, "Assessing the Greenhouse Gas Mitigation Potential of Urban Precincts with Hybrid Life Cycle Assessment."

to estimate the entire urban scope.[329] Further, without any changes to technology, economic system, urban design, or occupant lifestyle, the GHG emissions of the neighbourhood can be readily reduced by 31%. Most of the proposed avoided emissions are the result of reducing operational and transportation emissions through methods that shift some of their emissions into the embodied category (eg. the addition of PV panels).

The research highlights the role that urban design changes can have through its exclusion of this category of potential reduction, though some of the transportation emission reductions begin speaking to this impact. While some material substitutions and reductions were considered in embodied carbon reduction, overall zoning decisions which underpin the neighbourhood's composition remain stagnant. For example, if the floor area of detached houses (2723 units) were instead townhouses (194 m^2 vs 214 m^2 per unit in the study), the per capita embodied emissions of the neighbourhood would drop by 10%, or if they were instead apartment building units, per capita embodied emissions would drop by an additional 17% (approximately 8% of total emissions). These savings are calculated based on reduced floor area per unit, however there would also be construction efficiencies afforded by missing middle, mid- and high-rise construction.[330]

These embodied carbon reductions would also likely be accompanied by transportation related reductions. Yu et al. found that reducing vehicle journeys by a mere 15% and shifting 25% of car travel to bus would reduce the total neighbourhood emissions by approximately 8%.[331] Though the authors propose that these changes could occur under the pretense of no change to urban design or lifestyle, this does not seem entirely feasible given that a certain density of development is required for this mode shift to occur. Similarly to buildings, the strategies popularized by the World Green Building Council of: build nothing, build less, build clever, and build efficiently, all apply to vehicles as well.[332] The role of zoning falls into achieving the first two. By developing mixed-use, dense cities, we can remove or reduce the need for cars. Though electric vehicles (EVs) have significantly lower tailpipe (operational) emissions than internal combustion engines (ICE), they have greater embodied emissions as a result of their battery manufacturing. Embodied carbon accounts for approximately 18% of lifetime emissions for ICE cars (~7.5 tCO_2e) and up to 70% for EVs (~14 tCO_2e) in Canada.[333] At a project scale, these potential emission reductions are huge. Assuming a vehicle lasts for 10-12 years (and 200,000 km),[334] a vehicle will need to be

329. Lotteau et al., "Critical Review of Life Cycle Assessment (LCA) for the Built Environment at the Neighborhood Scale."

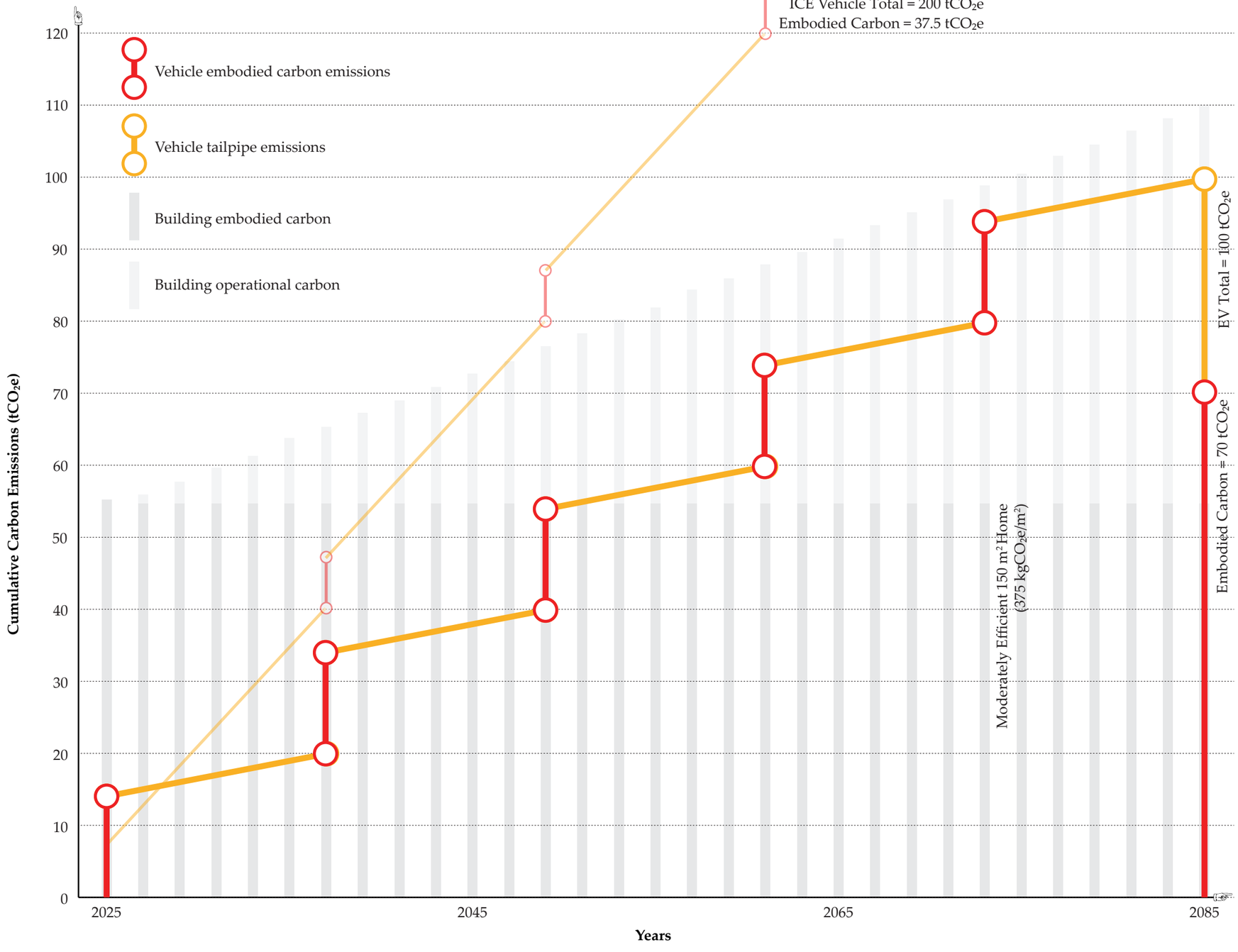
330. Rankin et al., "Embodied GHG of Missing Middle."

331. Yu, Wiedmann, and Langdon, "Assessing the Greenhouse Gas Mitigation Potential of Urban Precincts with Hybrid Life Cycle Assessment."

332. Alter, "Why Cars Are Like Buildings and Why Embodied Carbon Matters."

333. Hirz and Nguyen, "Life-Cycle CO2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems."

334. Ken Budd, "How Long Do Cars Last?"



f 3.16

Comparison of a typical home and the vehicles used to support it over a 60 year life cycle.

The data on EV and ICE vehicles presented by Hirz and Nguyen was adapted based on Canadian average electricity emissions. The home in this scenario has an embodied carbon of 375 kgCO2e/m2 and an area of 150 m2, the vehicles are assumed to last 12 years. Neither the building or cars account for maintenance or end of life emissions.

replaced five times in the lifespan of a building, for a total embodied carbon emission of 37.5 or 70 tCO_2e (200 or 100 tCO_2e including operational emissions) for ICE and EV cars respectively. This is between 50% and 187% of the total embodied emissions of the home it supports, when operational emissions of the vehicles are included, they eclipse the home value at 133% - 533% (assuming the home is 150 m^2 and 250-500 $kgCO_2/m^2$) (figure 3.16).

On the NBCC side of things, the spatial separation, limiting distances, and exposing building face requirements often require that the construction type and cladding type are of *noncombustible construction*. Barrier #5 provides an overview of the potential embodied carbon benefits of combustible construction, though the potential inclusion of combustible cladding may provide as much benefit given the many high-carbon options typically used (brick, aluminum, and glass).[335] The note associated with combustible cladding, A-3.1.4.8.(1), states the requirements are "intended to limit the potential for fire spread on the exterior cladding of buildings of combustible construction through the use of noncombustible finishes."[336] However, the associated functional statements and objectives read differently (F02,F03 – OP3), the purpose of noncombustible cladding is "to limit the severity and effects of fire or explosions **and** to retard the effects of fire on areas beyond its point of origin **so that** adjacent buildings are not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond the building of origin." While these conflicting purposes may simply be an example of misalignment, it is exemplary of the larger problem of the incongruency in the scope of the Code. Clarifying these requirements in combination with spatial separation could potentially lead to significant embodied carbon savings. Note A-3 (figure 3.12) elucidates the lack of basis with which the Code assumes firefighting capability which, if quantified, could have embodied carbon impacts as the result of reduced combustibility requirements.[337]

Further embodied carbon benefits of greater urban fire responsibility allocation lay within the prevention of fire loss (to all fire, but wildfire in particular). The 358 buildings (approximately 800 housing units) that were destroyed in Jasper when fire ripped through in 2024 account for approximately 60,000 tCO_2e lost to the atmosphere.[338] This may seem like an anomalous period but it represents only a fraction of the 2,400 buildings destroyed in Fort McMurray in 2016 (0.36 $MtCO_2e$).[339]

335. Magwood, Bowden, and Trottier, "Emissions of Materials Benchmark Assessment for Residential Construction."

336. Canadian Commission on Building and Fire Codes, "NBCC 2020," 3-229 Division B.

337. Canadian Commission on Building and Fire Codes, 3-225:226 Division B.

338. Cindy Tran, "Jasper Wildfire: Temporary Housing a Top Priority, $283 Million in Estimated Lost Property Value," Edmonton Journal, August 14, 2024, https://edmontonjournal.com/news/local-news/jasper-residents-prepare-to-return-home-officials-say-temporary-housing-will-be-a-top-priority. This ballpark figure is calculated through 800 units at 150 m2 and 500 kgCO2e/m2, which are all on the higher side to account for non residential buildings and variability in unit size.

339. "Fact Sheet: Climate Change and Wildfires in Canada."

Proposed Change

The issue of urban fire safety is complex and multi-faceted. Its history and development must be reckoned with in order to determine the assumptions made at the time of writing and whether this is still an appropriate contemporary response. Early fire bylaws created divisions between uses (that may have been effective in 1850), which were then codified into zoning documents with the overt purpose of discriminating against certain uses (particularly multi-unit residential) under the guise of fire safety. As fire safety regulation narrowed its scope to deal with buildings one-by-one through the NBCC, the contextual relationship of a building's fire risk to its urban context has become increasingly difficult to define and evaluate. Artifacts left in the Code suggest that the AHJ is responsible for final zoning decisions based on fire department capability, which both requires the AHJ to make complex risk assessments that they may not have the capacity to do and allows zoning decisions to continue to be made in the name of fire safety without quantifiable data to back them up. The purpose of this analysis is not to evaluate the applicability or critique the merits of zoning, it is to bring forth the relationship between fire safety and zoning in an effort to reconsider the latter with an updated sense of fire regulation and new consideration for embodied carbon.

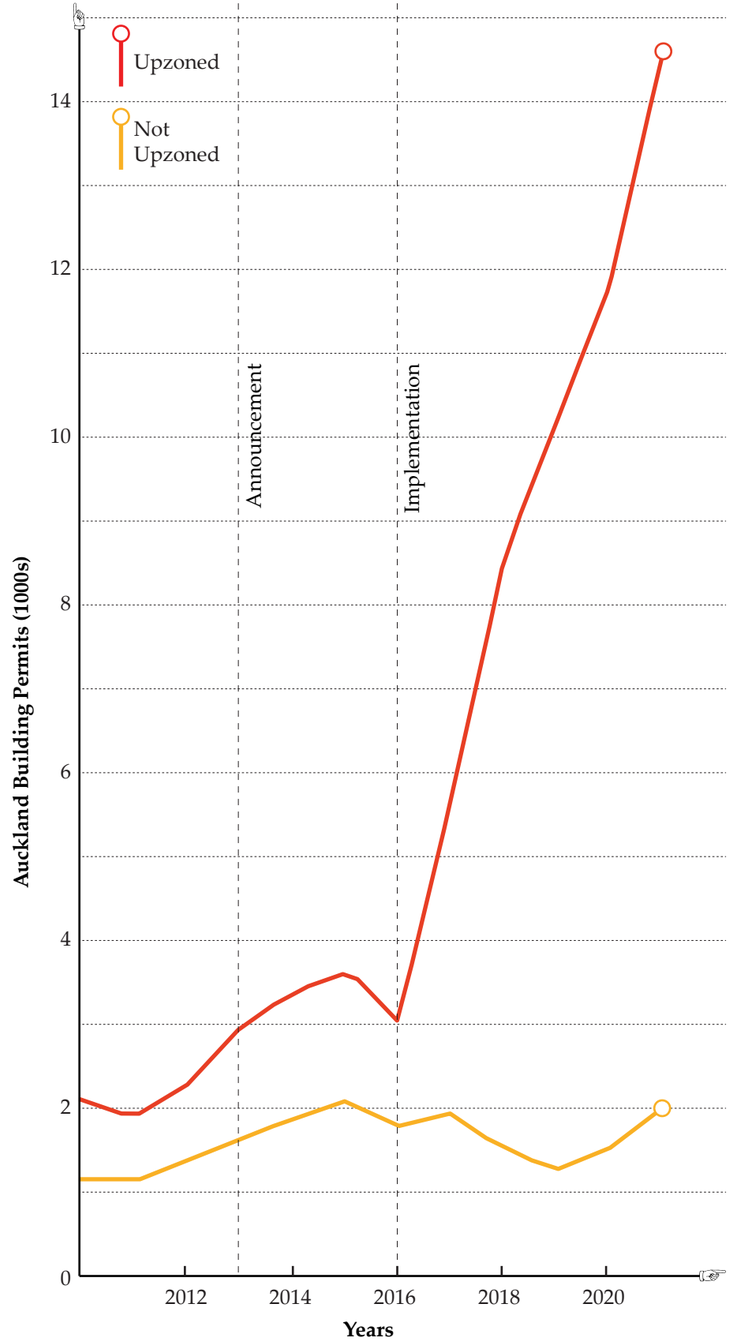
A holistic review of zoning by all AHJs (and particularly those with older bylaws) should be conducted to ensure that policies are reflections of current needs rather than holdovers from historical documents. New documentation must be written with a particular awareness of self-referential ideology – that a regulation is appropriate because it aligns new construction with the existing forms, that were informed in turn by old requirements. An important first step would be the development of a report on the historical lineage of specific contemporary zoning policies in an attempt to elucidate the reasoning behind current regulations. Following this, a set of objectives and functional statements should be created in a similar manner to the NBCC and ideally include performance metrics (e.g. decibel level, loading frequency). Quantifiable values could potentially allow any occupancy to exist in any part of the city, provided they meet the stated limits, enabling a quasi-market-based solution to develop the "best and highest use" of urban land. AHJs should compare contemporary objectives and performance metrics with historical reasoning to clearly lay out areas of misalignment, and finally, rewrite the zoning bylaw in order to enact the objectives.

This change has enormous potential to reduce embodied carbon emissions through the encouragement of efficient housing types, reduced demand for the manufacturing of personal vehicles, and reduced transport emissions. Upzoning (the allowance of taller and denser housing) has shown very promising effects at a large scale (figure 3.17),[340] though its impact is reduced as scale decreases.[341] Greater mixed-use zoning (the intermingling of commercial, office, and residential uses) has been evaluated as a feasible solution to reduce GHG (including embodied carbon) emissions[342] [343] regardless of transportation networks.[344]

On the NBCC side of things, a clear definition of the bounds of the Code in regard to assumed context, particularly regarding risk to adjacent buildings, spatial bounds of regulation, firefighting capability, and response time, is required in order to develop a science-based and quantifiable Code. This proposed change is in line with other literature that suggests a broader re-evaluation of the underpinnings of the NBCC.[345] [346] [347] While it is unclear whether the reconsideration of these requirements will have a positive impact on embodied carbon, similar research suggests that the NBCC is more conservative than necessary.[348] [349] Regardless, a determination of the basis of our assumptions is imperative in order to understand the level of fire safety in our buildings and move forward in a productive manner. Future research should focus on spatial separation and the relationship with fire departments with an eye towards the possible synergies with embodied carbon reduction (e.g. combustible cladding).

Further, the alignment of zoning regulations and building code, particularly regarding building size and construction relative to occupancy, has the potential to eliminate redundancy, clarify formal requirement, and limit embodied carbon implications. While zoning is only partially responsible for urban fire safety, it can play a strong role in aligning and enabling fire-safe construction to occur in the most efficient way possible. For example, sufficient water infrastructure in the areas zoned for occupancies which require sprinklers should be ensured. Similarly, if Barrier #1 is adopted, roads of reduced width should be planned in zones which limit height in alignment with the change. "Zoning is merely keeping the kitchen stove out of the parlor… It provides that houses shall be built among houses, apartments in apartment zones"[350] To borrow from the analogy above, now that homes have induction cook tops, smoke alarms, and fire extinguishers within reach, one entertains in the living room as much as the kitchen and the party is livelier for it.

340. Greenaway-McGrevy and Phillips, "The Impact of Upzoning on Housing Construction in Auckland."
341. Freemark, "Upzoning Chicago."
342. Hachem, "Impact of Neighborhood Design on Energy Performance and GHG Emissions."
343. Bibri, Krogstie, and Kärrholm, "Compact City Planning and Development."
344. Senbel et al., "Compact Development without Transit."
345. Calder, "Thesis Proposal: A Risk-Based Framework for Transitioning the National Building Code of Canada from Objective- to Performance-Based for Fire Safety."
346. Yuan, "Challenges Faced in Application of Fire and Life Safety Design in Current Canadian Building Code."
347. Fischer, "Societal Decision-Making for Optimal Fire Safety."
348. GHL Consultants Ltd, "Technical and Process Risks in 5 and 6 Storey Wood-Frame Buildings of Residential Occupancy."
349. Calder and Senez, "Review of Proposed Building Code Changes to Permit 5/6 Storey Wood-Frame Construction."
350. Metzenbaum, "The History of Zoning - A Thumbnail Sketch."



f 3.17

Comparison of building permits issued in Auckland by areas that were upzoned and not upzoned.

Though there are a number of factors which impact the number of building permits issued, Auckland presents a clear case study that upzoning does in fact boost construction. The graph offers a glimpse of what could occur in Canadian cities if given the chance. See source document for further analysis.

Interview with Conrad Speckert

BAS, M.Arch., Intern Architect, Single Exit Stair Researcher

You've been primarily researching single exit stair regulation, can you talk about some of the other regulations with large impact?

How does building typology arise as a direct result of regulation?

Can you talk about the difference between prescriptive-, objective-, and performance-based codes?

Is there anything that you think is missing from this conversation?

f 3.18

Excerpts from interview with Conrad Speckert on June 26, 2024.

See Appendix A for full transcript.

"There's been a lot of discussion about is the spatial separation of buildings, which is the side wall construction that you're allowed to do. Section 9.10.14. of the building code deals with spatial separation of buildings [other than houses] and 9.10.15. is spatial separation of houses. A house is defined as a building with not more than two units, so a two-unit building is allowed to do certain things that a three-unit building or four-unit building cannot. Now of course, the spatial separation of buildings is also for non-residential uses of small buildings. So, a warehouse stacked full of plywood requires the same spatial separation as three-unit house. This is to say that we've created these trigger levels, but there's a clear exemption for two-unit houses…

That is why in North America we see mostly houses and stacked townhouses - because they're all using the house definition to carve themselves out of having to do a whole bunch of other things. And I think, yes, maybe a three-unit building has a higher fire risk than a two-unit building in the sense that it contains more fire load, i.e. one additional kitchen. But the incremental additional safety requirements that come with three units are vastly [disproportionate], the scale jump is way more severe than you would think makes sense.

Spatial separation of buildings is a nuance where you then have to make the side walls non-combustible, and that's a bit awkward because you can do non-combustible construction as concrete, but you can also do it as steel studs with spray foam in between. If you do a fire test on a steel stud wall and you do a fire test on a wood frame wall with wood fiber installation or with mineral wool insulation between the [studs], the wood frame wall will beat the performance of the steel."

"These are massive pieces of land that could get cut up in any particular way, but because of this reason, they are cut up in exactly 600 square meter building area chunks. If you drive by, you'll see the kind of ugly roof details, right where the firewall separation is. All of it is because the companies building these wanted to do them in a way that wouldn't require them to be in Part 3, but to max out the Part 9 restrictions. So that's one example of building form directly derived from code thresholds."

"[W]ith this scale of projects, you often just don't want to have to go through the engineering reports, and consulting, and the "this fire department has this truck but that one's going to get decommissioned soon because our municipalities shrinking", or whatever the narrative is. Sometimes we push back on prescriptive codes because they seem frustrating, but at the same time, they actually make our lives easier, because if you look at some jurisdictions that only have performance-based code, it can be extremely laborious and confusing to navigate."

"If it's in the public's best interest to reduce embodied carbon and the amount of overall risk to all Canadians posed by embodied carbon exceeds that of fire safety, then we need to really think about it. The problem is that when someone dies in a fire, it goes in the media. It comes with visuals. It's very reactive and emotional. It's not like you can photograph embodied carbons impact on the population and write a Toronto Star article about it."

Building Scale Barriers

The preliminary decisions made in the design of buildings hold immense potential to reduce the embodied carbon of the resultant project. These qualities of form, structure, and circulation form the basis from which the building takes shape. In Canadian missing middle and mid-rise housing, most of these decisions are the result of prescriptive clauses in the Code which mandate the construction type, number of storeys, and number of exits. Until recently, these thresholds had not changed significantly, however new regulation stemming from the British Columbia Building Code has significantly influenced the reconsideration of these requirements.[351] [352]

The application of fire safety research has long been inhibited by conventional perceptions. At a large scale, the desire of regulators to have simple tests, rules, and limits for administrative clarity and convenience clashes with the nuance of real scenarios and the flexibility required to achieve ideal solutions.[353] Another consequence of developing thresholds is that they will be used in practice to the greatest degree possible; 7 storey buildings are rarely built because they exceed the 6 storey threshold and therefore must comply with the same requirements as a 12 storey building without recovering the cost associated with increased economy of scales.[354] The NBCC requires little change in requirements whether a building is 7 or 100 storeys, as both are classified as high buildings. It is very important that the definitions and thresholds within the Code are precise, enable desired results, and delimit consequential changes in fire safety without needlessly impacting embodied carbon.

Single egress buildings, used throughout the world, have been restricted to buildings of not more than 2 storeys in Canada. Consequently, the plan of residential buildings is largely determined through the requirement to have two means of egress, limiting floorplate efficiency and a number of other livability concerns.[355] Similarly, the definition for *building height* omits basement storeys, encouraging practitioners to build below grade to maximize the floor area allowed under NBCC building height thresholds. This limit is particularly important to define as the decision to build a storey below grade may be 1.6 times more carbon intensive than above grade (see Barrier #4). These savings are largely the result of

351. Ministry of Housing, "B.C. Builders Can Now Use Mass Timber in Taller Buildings."
352. Ministry of Housing, "British Columbia Building Code Revision 3."
353. Law and Beever, "Magic Numbers and Golden Rules."
354. Dreeson, "Canada's Building Codes and Standards Need to Get with the Times."
355. Eliason, "Unlocking Livable, Resilient, Decarbonized Housing with Point Access Blocks."

a change to timber construction, which may not be permitted given the total building height. Recent changes to the maximum height of wood buildings have enabled lower carbon construction than previously, however, these new limits may also be more reductive than necessary. Timber buildings, both light wood frame and mass timber hold enormous potential to reduce the embodied carbon of a project, [356] but the main barrier to the adoption of wood as a structural material is the building code – cited by 40% of projects as the reason they decided not to pursue it.[357]

356. Himes and Busby, "Wood Buildings as a Climate Solution."
357. Gosselin et al., "Main Motivations and Barriers for Using Wood in Multi-Story and Non-Residential Construction Projects."

Barrier #3:
Single Exit Stair

Regulation and Interpretation

Single stair buildings have been a significant area of focus in the last five years in North America as a method to deal with both the housing crisis and increase the standard of living. Proponents argue that this type of housing makes missing-middle and mid-rise housing easier to build; the relatively small floorplates allow small-scale sites to become a viable option for development which, in turn, alleviates the large capital requirements for land assembly and large-scale construction budgets.[358] [359] [360] As a building typology, single stair buildings have been built across the world and continue to be used almost exclusively across Europe. Within North America, they were used extensively in the latter part of the 19th and early 20th centuries, but ceased following the Triangle Shirtwaist Factory fire in 1911. This fire, and numerous others, including the UK's Grenfell Tower fire in 2017, are used as examples of the catastrophic outcomes of a single means of egress.

The requirements governing egress are outlined in NBCC section 3.4. (for Part 3 buildings) and section 9.9. (for Part 9 buildings). They stipulate that two means of egress are necessary for any building greater than 2 storeys (with limited exceptions) (figure 3.19). This requirement is applied equally for buildings covered by Part 9 as by Part 3, the effect of which is that a 3 storey building must adhere to the same basic egress rules as a 50 storey one. The two stair regulation is accompanied by an ensemble of other requirements like distance between exits, travel distances, location of exits, exit widths, exit heights, fire separation, and signage.

The impact of this broad stroke application is exacerbated by the spatial implication of the regulation; two-egress buildings tend towards a hotel typology, where a corridor runs down the middle of the building connecting the stairwells at either end, with doors to units on both sides of the hallway (typically referred to as a double-loaded corridor). Single egress buildings on the other hand, tend to locate the vertical circulation in the center of the building with a short hallway to access units. In order to increase the efficiency of two-egress buildings, units are deepened, increasing the distance

f 3.19

Excerpts from NBCC 2020.

358. Speckert, "The Second Egress."

359. Eliason, "Unlocking Livable, Resilient, Decarbonized Housing with Point Access Blocks."

360. Smith and Mendoza, "Point Access Block Building Design."

1.4.1.2. Defined Terms

Exit means that part of a *means of egress*, including doorways, that leads from the *floor area* it serves to a separate *building*, an open public thoroughfare, or an exterior open space protected from fire exposure from the *building* and having access to an open public thoroughfare. (See Note A-1.4.1.2.(1).)

Means of egress means a continuous path of travel provided for the escape of persons from any point in a *building* or contained open space to a separate *building*, an open public thoroughfare, or an exterior open space protected from fire exposure from the *building* and having access to an open public thoroughfare. *Means of egress* includes *exits* and *access to exits*.

3.4.2.1. Minimum Number of Exits

1) Except as permitted by Sentences (2) to (4), every *floor area* intended for *occupancy* shall be served by at least 2 *exits*.

2) A *floor area* in a *building* not more than 2 *storeys* in *building height*, is permitted to be served by one *exit* provided the total *occupant load* served by the *exit* is not more than 60, and

a) in a *floor area* that is not *sprinklered* throughout, the *floor area* and the travel distance are not more than the values in Table 3.4.2.1.-A, or

b) in a *floor area* that is *sprinklered* throughout

i) the travel distance is not more than 25 m, and

ii) the *floor area* is not more than the value in Table 3.4.2.1.-B.

3) Except as permitted by Sentence (4), if Sentence (2) permits a single *exit* from a *floor area* classified as Group B or Group C *occupancy*, the *exit* shall be an exterior doorway not more than 1.5 m above adjacent ground level.

4)…

3.4.3.2. Exit Width

1) Except as permitted by Sentence (3), the minimum aggregate required width of *exits* shall be determined by multiplying the *occupant load* of the area served by

a)...

c) 9.2 mm per person for

i) rampswith a slope ofmore than 1 in 8, or

ii) stairs, other than stairs conforming to Clause (b).

2)…

8) The minimum widths of *exits* shall conform to Tables 3.4.3.2.-A and 3.4.3.2.-B.

Group C: 1100 mm for e*xit* corridors and passageways, *ramps*, and *stairs*.

between the hallway and the outside of the building. This typically results in a rectangular-shaped floor plan, where each unit has a limited amount of window area and must allocate significant floor area to in-unit circulation. Single-egress buildings on the other hand, tend to gravitate towards a square-shape, which may be aggregated to form a rectangle or various other shapes (figure 3.20).

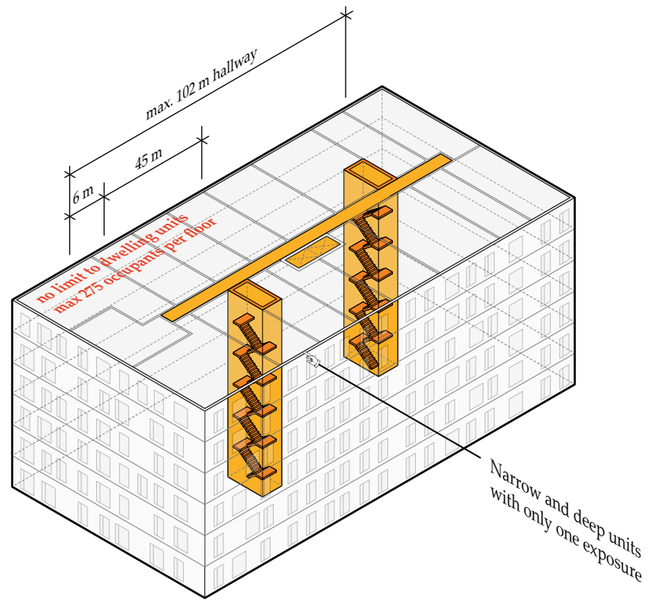
From a livability perspective, these differing typologies offer one significant difference from one another. Single-egress building units tend to be dual-aspect, meaning that they have windows on more than one side, while double-egress building units are typically single-aspect. The additional window area of single-egress building units allows for two important things to occur; first, it is easier to accommodate units with more bedrooms (an increasingly important characteristic as North American cities tend to lack housing types for families) and second, it is easier to manage environmental conditions (another increasingly important factor as we face a warming climate). Dual-aspect units allow for cross-ventilation, more natural daylight hours, and offer protection from noise if one part of the unit faces a busy thoroughfare. Additionally, a central circulation core improves the sense of community within a building and can encourage a more active lifestyle.[361]

Speckert and Hine initiated the first formal review of this regulation through a code change request in April, 2022, which outlines the proposed change and accompanying additional safety features.[362] Similarly, Jensen Hughes was engaged by the British Columbia Housing Ministry to develop a report on options and implications of including single stair buildings in the British Columbia Building Code (BCBC) which also proposes additional safety features.[363] Many of these recommendations were followed when the BCBC was amended on August 27, 2024 to allow single exit stair building design up to 6 storeys (figure 3.28).[364]

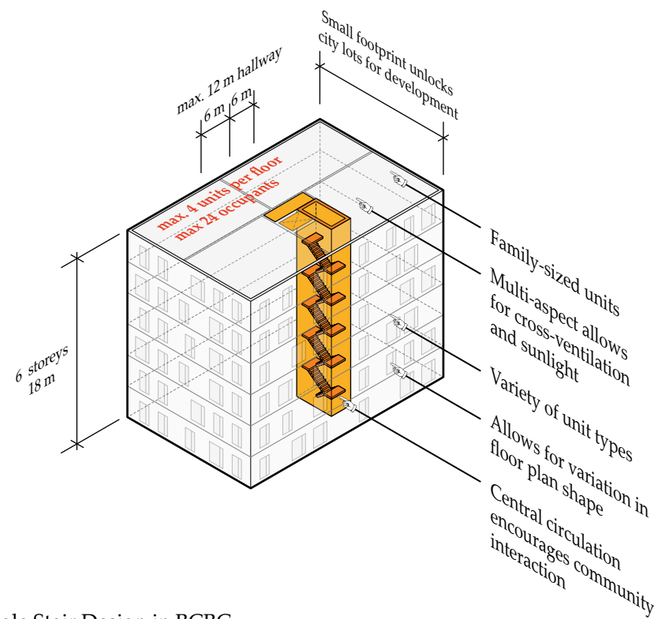
Fire Safety Impact

The primary purpose of two exit stairs is to provide for an alternative means of egress if one of the stairways is blocked or obstructed. A review of fires in British Columbia, Alberta, Australia, New Zealand, and the UK, revealed that approximately 8-10% of fires in apartment buildings may originate in egress routes, however fires rarely spread beyond their room of origin, particularly when fire sprinklers and smoke alarms are provided.[365] Therefore, when

361. Eliason, "Unlocking Livable, Resilient, Decarbonized Housing with Point Access Blocks."
362. Speckert, "The Second Egress," April 18, 2022.
363. Heikkila, Ghosh, and Chen, "Single Egress Stair Building Designs."
364. Ministry of Housing, "British Columbia Building Code Revision 3."
365. Heikkila, Ghosh, and Chen, "Single Egress Stair Building Designs."



a) Typical Two Stair Design



b) Single Stair Design in BCBC

f 3.20

Comparison of a typical two-stair building complying with NBCC 2020 and a single-stair building complying with BCBC 2024.

See proposed change section for detailed outline of change.

looking to the additional life safety measures to include when removing an alternative means of egress, emphasis should be placed on reducing fire risk in egress routes and controlling fire spread. Extensive work is underway to allow single-egress buildings across jurisdictions within Canada and the USA. Although Seattle, New York City, and the Island of Oahu are the only jurisdictions in the USA that currently allow single stair buildings, Washington and California are amongst a handful of states looking at the possibility of allowing them.

Within the NBCC, egress requirements have largely remained unchanged since the first edition in 1941.[366] These requirements and subsequent adjustments are outlined in figure 3.21. Notably, British Columbia recently amended their building code to include single stair buildings and the National Research Council is conducting research to inform single egress code changes for inclusion in the 2030 NBCC.[367]

Before the 1850s, there were almost no laws which governed occupant egress in North America. Buildings were rarely taller than 3 storeys and occupants could be rescued using ladders reaching to windows or survive the jump to safety in most cases. As building heights increased through the middle of the 19th century, fire safety became more complex in order to deal with larger occupant loads, larger volumes of flammable material, and heights in excess of the tallest ladders. Even though these additional risk factors multiplied on top of one another, the legal precedent of North America was such that building owners had no legal obligation to address fire safety.[368] Redundant safety features, such as second stairs or larger hallways, added cost and reduced space – moreover, the public did not demand these additional measures. As with the past, significant fires and fire deaths due to inadequate exits spurred on the development of contemporary requirements.[369]

In New York City, tenement house fires were a common occurrence and the danger to life soon proved significant enough (sparked by the 1860 tenement fire on Elm Street which killed 30) that New York City introduced a comprehensive building code in 1860 which included the provision that large apartment houses (9 units or more) must have a fireproof stair tower or "fireproof balconies on each story on the outside of the building, connected by fireproof stairs."[370] The sentence describes what we now know as the ubiquitous New York fire escape. This precision of language is important because when that sentence was later removed and simply called for "fire

366. National Housing Administration and National Research Council, "NBC 1941."

367. Heikkila, Ghosh, and Chen, "Single Egress Stair Building Designs."

368. Sara E. Wermiel, *The Fireproof Building: Technology and Public Safety in the Nineteenth-Century American City* (Baltimore & London: The Johns Hopkins University Press, 2000), 188.

369. Wermiel, *The Fireproof Building*, 188-91.

370. Wermiel, 190.

Building Code	Max Building Height (Storeys)	Max Building Area	Max Travel Distance to Exit	Sprinklered	Max Occupant Load per Floor
1927 UBC	2	278 m2 (3000 ft2)	N/A	No	N/A
1941 NBC	3	278 m2 (3000 ft2)	45 m	No	100
1953 NBC	Any if NC 3 if C	93 m2 (1000 ft2)	30.5 m (100 ft) if NC 22.8 m (75 ft) if C	No	60
1960 NBC					
1965 NBC					
1970 NBC	NP	NP	NP	NP	NP
1975 NBC					
1977 NBC	2	93 m2 (1000 ft2)	15.2 m (50 ft)	No	60
1980 NBC	2	100 m2	15 m	No	60
1985 NBC					
1990 NBC					
1995 NBC	2	100 m2 150 m2 if SP	15 m 25 m if SP	No	60
2005 NBC					
2010 NBC					
2015 NBC					
2020 NBC					

f 3.21

Summary of historical code requirements for single stair buildings in Canada.

Note that the 1927 Uniform Building Code (UBC) did not have any legal bearing in Canada; its inclusion is to show a historical continuity.

NC = noncombustible;
C = combustible;
NP = not permitted;
SP = sprinklered.

escapes," a plethora of devices came roaring into existence; baskets on pulleys, drop-ladders, and winged inventions all counting as acceptable solutions (figure 3.22).[371]

An 1867 amendment introduced the requirement that an egress stair be located within the building and protected by fireproof brick walls from the foundation to the roof. This requirement was relaxed in 1871, requiring the brick enclosure to only reach the underside of the second storey. At the same time, legislators expanded the requirement for fire escapes, likely bowing to building owners' preference for a less expensive solution.[372] This seemingly innocuous retraction of a single fire protected stairway in favour of a second egress route in 1871 may appear entirely trivial, but in ceding to financial concerns of the time, this regulation cemented the second egress requirements seen today.

Egress laws evolved significantly in the realm of the public buildings; Chicago's Iroquois Theatre fire (1903) is the deadliest fire in American and Canadian history.[373] [374] Despite being built of fireproof construction, a fire which originated on stage spread quickly, killing 602 people – largely through suffocation by smoke and trampling in the chaos as a result of insufficient exits (poorly marked, opened inwards, and some were locked). It illustrated that the combustion of building contents can be incredibly deadly even if the building's structure remains untouched. Similarly, the Triangle Shirtwaist Company factory building (1911) was fireproof, though fire spread quickly in it too, with locked exits (and undersized fire escapes) trapping workers on the 9th and 10th floors. A reporter stated that the building "shows now hardly any signs of the disaster that overtook it. The walls are as good as ever; so are the floors; nothing is the worse for the fire except the furniture and 14[6] of the 600 men and girls that were employed in its upper three stories."[375]

These two fires, and particularly the latter, spurred the introduction of exiting requirements into building codes and marked an important shift in the role of regulation; property protection was no longer the only focus of fire prevention, life safety began to take the primary focus.[376] The two stair requirement first appears in the Uniform Building Code of 1927: "provided, that in no case shall there be less than two stairways serving each floor for each building three stories or more in height." [377] Fire escape laws spread quickly across Canada and North America and expanded to include all building types.

The fire relationship between allowable single stair building height and fire deaths per capita is tenuous at best. It is difficult to

371. Young, "The Creative and Forgotten Fire Escape Designs of the 1800s."

372. Wermiel, *The Fireproof Building*, 191.

373. NFPA, "Deadliest Single Building/Complex Fires and Explosions in the US | NFPA."

374. Halliday, "Fire Disasters in Canada."

375. "141 Men and Girls Die in Waist Factory Fire; Trapped High Up in Washington Place Building; Street Strewn with Bodies; Piles of Dead Inside; The Flames Spread with Deadly Rapidity Through Flimsy Material Used in the Factory."

376. Kaplan, "Safety and Building Codes."

377. International Conference of Building Officials, *Uniform Building Code 1927*.



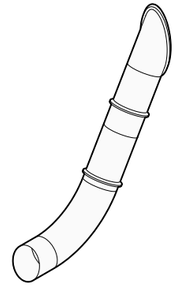
a) Parachute and padded overshoes



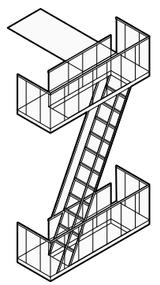
b) Rope ladder affixed to interior floor



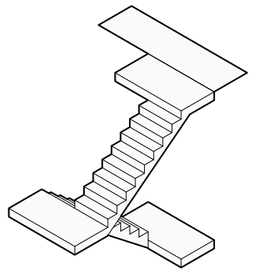
c) Extendable wheeled ladder



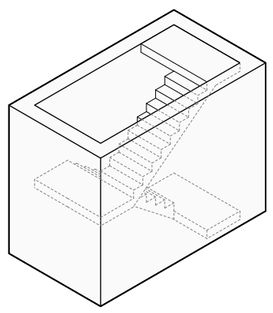
d) Fire escape chute/slide



e) Exterior fire escape



f) Additional interior stair



g) Pressurized stair core

f 3.22

Redundant egress routes throughout time.

These solutions are intended to add a layer of safety in an emergency scenario and work in addition to the single internal stair that is required for day-to-day circulation. Note that illustration h) denotes the pressurized core around the single internal stair, not an additional stair. The illustrations are intended to show a range of acceptable solutions but do not encompass all manners enhancing the safety of egress from a building.

ascertain the degree to which single stair building height affects life safety, given that numerous other factors beyond egress requirements impact the level of risk. Some of these include: building materials, occupant lifestyles (cooking, smoking, alcohol consumption, etc.), suppression systems, evacuation procedures, and occupant characteristics (age, health, etc.). [378] Data produced by the International Association of Fire and Rescue Services (CTIF: Comité Technique International de prevention et d'extinction de Feu) in Report 24 (2019) and Report 29 (2024), was reorganized and analyzed.[379] [380] Incomplete data was removed from the set (Israel, Austria, Belgium, Greece, and Thailand) as were countries with large outlier stats which indicate an inconsistency of collection or poor fit with the Canadian context (Slovenia, Bangladesh, Belarus, and Russia). Canadian mortality figures were compared against Statistics Canada data to verify and fill in the table. In Canada, fire deaths are tending to increase, with the average increasing from 158 (2013-2017) to 178 (2018-2021) per year.[381] The primary relationship explored by figure 3.23, is the correlation between maximum allowable single stair building height and a country's fire deaths per capita. In order to approximate other contributing factors, further layers of data to the set are needed: the number of career firefighters per capita (which approximates both the degree to which a country relies on active suppression and acceptable risk) and the number of deaths per fire (which approximates the speed at which fires spread and the levels of egress redundancy).

It is clear through the graph that there is no absolute trend, which indicates that single stair regulation is not inherently dangerous. In general, the fire death rate increases as single stair regulations become more restrictive, although there are low fire death rates at all allowable building heights. Similarly, the number of deaths per fire tends to increase with increasing single stair restrictions, which refutes the presupposition that single stair buildings trap people more easily than two stair buildings. The number of career firefighters also tends to increase with increasing single stair restrictions, although it does not correspond with a lower fire death rate, pointing to a misplaced emphasis on active suppression. It is important to note that firefighting tactics (including the possibility of elevator use are not considered in this analysis and that a change to existing practice would be necessary in order to accommodate the proposed change.

378. Kobayashi, "The History of Fires and Firefighting in Japan."

379. Brushlinsky et al., "World Fire Statistics Report 24," 24.

380. Ahrens, Sokolov, and Wagner, "World Fire Statistics Report 29," 29.

381. Statistics Canada, "Fire-Related Deaths and Persons Injured, by Cause of Death or Injury and Reason for Non-Evacuation."



f 3.23

Maximum allowable single stair height compared to fire death rate, deaths per fire, and career firefighters per capita.

Japan's fire death per capita is relatively normal (1.23 fire deaths per 100,000 inhabitants), while its deaths per 100 fires is exceedingly large (3.77 compared to the next largest 1.31) and, counterintuitively, their number of career firefighters is large (128 firefighters per 100,000 inhabitants, compared to Canada's fairly average 73). There are a number of factors at play which contribute to this discrepancy: arson accounts for approximately 30% of know fire causes during the time period analyzed, while an aging population and more frequent storms have likely counteracted the introduction of fire safety measures. The fire death per capita has been trending downwards, reaching 1.17 in 2022. Reporting standards may also differ between countries and introduce uncertainty.

Embodied Carbon Impact

While there are many differences between the single stair and two stair designs which have embodied carbon implications, none are more important than compactness.[382] Those in favour of single stair buildings often present floorplate efficiency as one of the ways in which they are superior to the double loaded corridor, although at the time of writing no literature supported this conclusion. A very recent study suggests that although single egress buildings have the potential to be more floorplate-efficient (especially on smaller lots), most built projects show little difference in efficiency from two stair buildings.[383] The comparison of single stair and two stair building designs is not entirely possible in an apples-to-apples manner, given their differences in form and size however, it is still a worthwhile endeavour. To carry out this comparison, this thesis performs two studies to compare their floorplate efficiency. First, existing floor plans of each building type are analyzed regardless of their dimensions, then a floorplate of each type with identical dimensions are compared (figure 3.24, 3.25, and 3.26). In the second study, to compare an equal footprint and floor area, the single stair building must be repeated with their sidewalls forming a party wall (figure 3.27). This form reduces the single stair advantage of multi-aspect units (which includes more bedrooms and passive benefits) in favour of reducing surface area and structural redundancy. The comparison assumes that the envelope and structure type are identical between buildings and only considers at the floor area differences.

Floorplates were divided into two parts, living area and service area. Service area was defined as all the area constrained within the walls of the corridors, stairways, elevators, and service closets. Living area is defined as the floor area enclosed by the exterior walls that is not service area (balconies are excluded from this study). Floorplate efficiency was calculated by comparing the net living area to the total floor area in order to determine the percentage of construction that contributes directly to occupancy. Using living area as a quantifier excludes public and semi-public spaces that might contribute to the total space used by those in the building.

Floor plans for two stair buildings were sourced through various architecture publications and architecture firm websites, and selected by location (Toronto) and height (4-9 storeys). Single stair buildings were sourced from secondegress.ca and social media. The majority of single stair examples are located within Europe, with one example

382. John Straube, "BSD-061: The Function of Form - Building Shape and Energy."

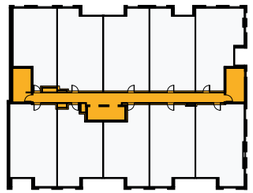
383. Utile, "Legalizing Mid-Rise Single-Stair Housing in Massachusetts."

Name	Location	Number of Storeys	Floor Area (m^2)	Sellable Area (m^2)	Service Area (m^2)	Floorplate Efficiency (%)	Number of Bedrooms	Floor Area (m^2) per Bedroom	Embodied Carbon (tCO_2e) per Person
Oben Flats	Toronto	6	793	712	81	89.8	12	**66.1**	16.5
Wonder Condos	Toronto	9	4143	3517	626	84.9	70	**59.2**	14.8
Junction House	Toronto	9	1564	1425	139	91.1	26	**60.2**	15.0
Duke Condos	Toronto	7	1400	1281	118	91.5	21	**66.7**	16.7
La Defense-Nanterre	France	13	957	849	108	88.7	26	**36.8**	9.2
Lubango Centre	Angola	12	462	429	34	92.7	8	**57.8**	14.5
Trum-mens Strand	Sweden	8	272	256	17	93.9	7	**38.9**	9.7
Urban Housing	Austria	8	424	384	40	90.6	9	**47.1**	11.8
Le Bois Habite	France	6	416	381	35	91.6	9	**46.2**	11.5
The Belmont	USA	7	208	180	28	86.7	5	**41.6**	10.4

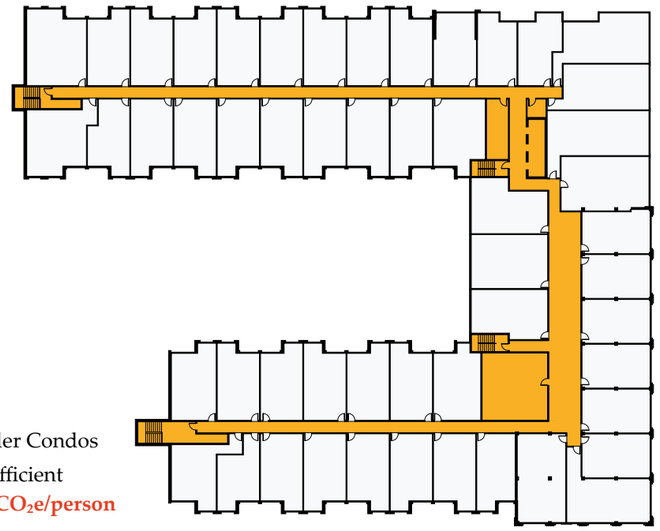
f 3.24

Two stair and single stair project floorplate comparison.

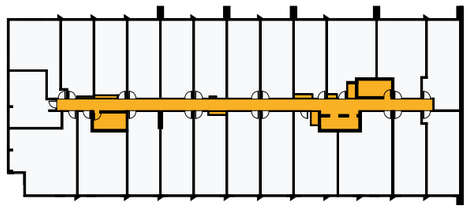
While multiple single stair cores can be strung together (La Defense-Nanterre) they generally have smaller floorplates and less bedrooms per storey than two stair buildings.



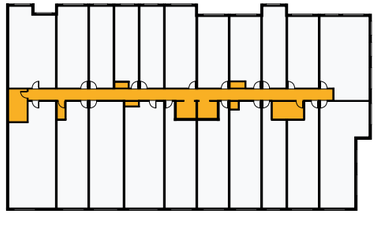
Oben Flats
90% efficient
16.5 tCO_2e/person



Wonder Condos
85% efficient
14.8 tCO_2e/person

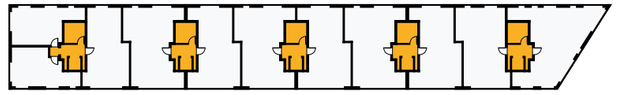


Junction House
91% efficient
15.0 tCO_2e/person

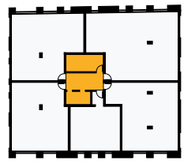


Duke Condos
92% efficient
16.7 tCO_2e/person

f 3.25
Floorplate efficiency of two stair buildings in Toronto.



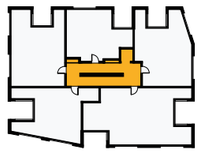
La Defense-Nanterre
89% efficient
9.2 tCO_2e/person



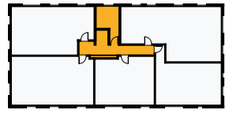
Lubango Centre
93% efficient
14.5 tCO_2e/person



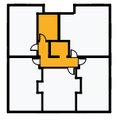
Trummens Strand
94% efficient
9.7 tCO_2e/person



Urban Housing
91% efficient
11.8 tCO_2e/person

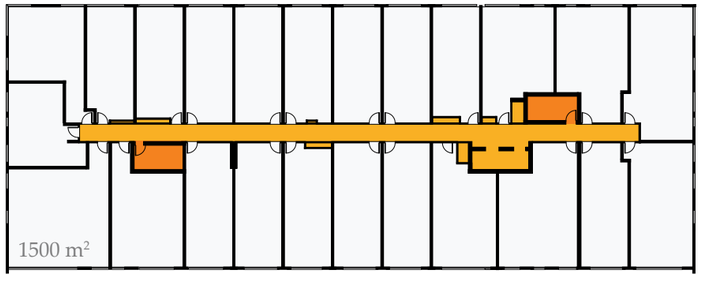


Le Bois Habite
92% efficient
11.5 tCO_2e/person



The Belmont
87% efficient
10.4 tCO_2e/person

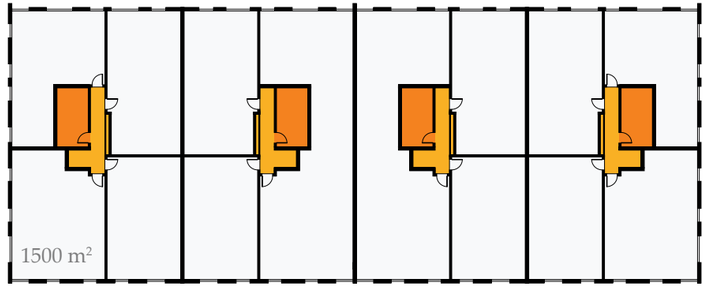
f 3.26
Floorplate efficiency of single stair buildings across the world.



Hypothetical two stair design

91% efficient
26 bedrooms
57.7 m^2 per bedroom

14.4 tCO_2e/person



Hypothetical connected single stair design

91% efficient
28 bedrooms
53.6 m^2 per bedroom

13.4 $kgCO_2e$/person

f 3.27

Comparitive analysis of two stair and single stair buildings with equal floor area

These hypothetical designs have an area of 1500 m2 in order to evaluate the applicability of single stair buildings relative to two stair designs in the Group C, up to 6 Storeys, Sprinklered category. Note that embodied carbon is highly sentative to changes in the number of bedrooms at this scale.

each from Africa and North America. Additionally, it is important to note that many of these examples would not comply with the single stair regulation proposed by Speckert and Hine. In all cases, floor plans were selected to represent the typical floor of each project, and the construction type varies between projects. Bedrooms are defined as sleeping rooms with a window; "dens" are excluded though they are commonly used as bedrooms in North American construction. While the occupancy of dens may be estimated, this thesis takes the position of not compromising livability in favour of carbon (we could all live in a single, large, windowless room). The study does not account for the higher carbon intensity of stairwells and elevators compared to corridor space, as the impact of this exclusion is likely to be minimal given the similarity in floorplate efficiencies.

Other differences in embodied carbon between the two types involve surface area (which is touched upon in Barrier #4 Building Height Definition) based on building geometry, structural differences (which are difficult to quantify), and differences in embodied carbon intensity based on program (two stair buildings tend to have more kitchens and bathrooms per person than single stair, which are highly carbon intensive compared to a bedroom or living room).

The study shows that while the assumption of inherently more efficient floorplates is wrong, single stair buildings are significantly more efficient in terms of floor area per bedroom and the corresponding embodied carbon per person, up to 55% less. At a whole building scale, this could amount to 900 tCO_2e saved (assuming a 6 storey building with 10 bedrooms per floor). Relatively shallow, and multi-aspect units in the single stair buildings allow for significantly more bedrooms for a given floor area, although these floorplates tend to be smaller which might have a corresponding increase in embodied carbon as structural efficiency is reduced.

Proposed Change

The NBCC fails to recognize single stair buildings as acceptably fire-safe, regardless of additional layers of life safety provisions. This assumption rests upon a series of tragedies over the past 100 years (each of which involved a number of contributing factors other than a single exit), and largely remains unchanged since its inclusion in the first NBCC (1941). Further, the Code has not acknowledged the breadth of solutions which alleviate risk and allow for single stair buildings to be constructed across Europe (and some US

	Perry (2024)	BCBC (2024)	Jensen Hughes (2024)	Speckert and Hines (2022)
Max Building Height (Storeys)	6	6	6	6
Sprinklered	Yes, including balconies, decks, and covered patios	Yes, including balconies, decks, and covered patios	Yes, including balconies, decks, and covered patios	Yes. Notes that including balconies may be appropriate
Fire Alarm	Yes, automatic notification of fire department	Yes, only sounding within applicable suite	Yes, only sounding within applicable suite	Yes, automatic notification of fire department
Occupant Load per Storey	30	24	N/A	60
Number of Units per Storey	N/A	4	N/A	4
Max Unit Size	N/A	N/A	N/A	150 m2
Limits to Smoke Movement	Pressurized exit stair shaft, vestibule, or exterior passageway	Pressurized exit stair shaft or vestibule	Pressurized exit stair shaft and/or public corridors	Pressurized exit stair shaft
Exit Discharge	Direct to street	Direct to street, within 15 m and facing the fire access route	Direct to street, within 15 m and facing the fire access route	N/A
Stair Width	1100 mm stair, 1500 mm landing	1500 mm	N/A (assumes 1100 mm)	N/A (assumes 1100 mm)
FRR	2 hour	2 hour	2 hour	N/A
Unit Door Rating	45 minute fire-protection	45 minute fire-resistance	45 minute fire-protection	45 minute fire-protection
Construction Type	25 FSR	Noncombustible or 25 FSR	Noncombustible	N/A

f 3.28

Summary of proposed changes to allow single stair buildings.

The 6 storey maximum building height corresponds with the maximum height before NBCC high building requirements kick in. Spinklering of balconies, decks, and projections is based on Calder and Senez's 2016 study of "The Key Modes of Fire Spread in Wood-Framed Apartment Buildings"

jurisdictions). The additional measures to proposed change are informed by the changes proposed by Speckert and Hine (2022), Jensen Hughes (2024), and the BCBC (2024), as well as a review of building codes in other jurisdictions, and studies of fire safety in residential buildings:

1. *Buildings* of *residential occupancy* are permitted to have a single exit, this applies only to *buildings* that
    a. Are not more than 6 *storeys* in *building height* (or proposed height in Barrier #4),
    b. Are *sprinklered* throughout, including: balconies, decks and covered patios
    c. Are equipped with a *fire alarm* system which automatically notifies the fire department
    d. Do not exceed an *occupant load* of 30 persons per *storey*
    e. Have an exit stair that
        i. Discharges directly to the exterior (no lobby discharge)
        ii. Has an enclosure with a 2 hour fire separation
        iii. Has a smoke control measure, such as pressurization, vestibule, or exterior passageway
    f. *Suite* doors that open onto the corridor must have a 45 minute fire-protection rating
    g. Have a *travel distance* from
        i. Any part of the *floor area* to an *exit* not more than 25 m, and
        ii. Each *dwelling unit* to an *exit* of not more than 6 m.

While the additional life safety measures set out by this thesis are similar to the above reports, there are a couple of distinct differences: no maximum dwelling units per storey (4 proposed by Speckert and Hine and BCBC), no maximum dwelling size (150 m^2 proposed by Speckert and Hine), no noncombustibility option for the stair core (suggested by Jensen Hughes and BCBC), and an altered minimum stair width requirement (1100 mm assumed by Speckert and Hine and Jensen Hughes, 1500 mm by BCBC) (figure 3.28). Including a maximum number of dwelling units and unit size is intended to reduce the floorplate size (to a limit of 600 m^2) and limit the number of potential fire causes (mainly kitchens). These floorplate size limits are better addressed by the maximum building areas listed

in subsection 3.2.2. Building Size and Construction Relative to Occupancy and the maximum *travel distances* suggested by the code change which do not delimit individual unit sizes (the 150 m^2 unit size proposed by Speckert and Hine would limit the inclusion of larger family-sized units). Potential fire ignition points are addressed through bolstering dwelling unit door fire-protection ratings which reduces the chance of fire spread while capping the number of units severely limits the application of this building type. As discussed in Barrier #7, the relative combustibility of a wall assembly is difficult to accurately define and does not necessarily improve fire safety. The purpose of this provision proposed by Jensen Hughes and implemented by the BCBC (with the alternative option of not more than 25 FSR) is likely to safeguard the stair core against any chance of fire spread, however this is better addressed by the inclusion of a fire separation requirement and FSR (2 hour FRR and 25 FSR is proposed by this thesis).

Barrier #4:
Building Height Definition

Regulation and Interpretation

Building height was one of the earliest building regulations and remains one of the most heavily regulated aspects of our built environment. Initially a matter of daylighting, views, and sanitation, the distance to the ground quickly became an issue of life-or-death in the late 1800s as building heights quickly increased. Regulations often used the upper limits of firefighting control as the maximum height in order to account for occupant egress and fire control.[384]

While the *building height* limitations of *combustible construction* will be discussed in the following chapter, the way in which we measure *building height* is also of particular note. The issue of defining a building's height is not purely semantic, it has a large impact on the form and construction typology of the buildings it governs. Systemically, the current definition encourages below grade construction, which impacts livability, construction cost, and embodied carbon costs, all without improving fire safety. Further, it is levied unevenly between construction types to the detriment of combustible buildings.

Article 1.4.1.2. Defined Terms provides the definitions which apply throughout the NBCC (figure 3.29). Similarly to many of the definitions, *building height* requires the reader to discern the meaning through three supporting definitions: *first storey*, *storey*, *grade*, and one note: grade. Simply put, *building height* is defined as the number of storeys counted from the uppermost floor that is less than 2 meters above the average level of ground surrounding the building. This definition seems fairly reasonable until it is evaluated for its purpose; *building height* is used throughout the code to limit the size of buildings as a means of fire control. It is used as a proxy for volume (allowable *building area* is a function of height) and ease (effectiveness) of firefighting. The "grade" note reveals to the reader the intent behind determining *building height* as a function of *grade*; the uppermost floor of the building is not to be more than the specified number of storeys plus 2 meters from the surrounding *grade* in order for firefighting to proceed as designed (figure 3.30).

f 3.29

Excerpts from NBCC 2020.

384. Calder and Senez, "A Historical Perspective on Building Heights and Areas in the British Columbia Building Code."

1.3.3.3. Application of Part 9

1) Part 9 of Division B applies to all *buildings* described in Article 1.1.1.1. of 3 *storeys* or less in *building height*, having a *building area* not exceeding 600 m2, and used for *major occupancies* classified as...

1.4.1.2. Defined Terms

Building height (in *storeys*) means the number of *storeys* contained between the roof and the floor of the *first storey*.

First storey means the uppermost *storey* having its floor level not more than 2 m above *grade*.

Grade means the lowest of the average levels of finished ground adjoining each exterior wall of a *building*, except that localized depressions need not be considered in the determination of average levels of finished ground. (See *First storey* and Note A-1.4.1.2.(1).)

Storey means that portion of a *building* that is situated between the top of any floor and the top of the floor next above it, and if there is no floor above it, that portion between the top of such floor and the ceiling above it.

A-1.4.1.2.(1) Grade

Localized depressions that need not be considered in the determination of the elevation of grade include such features as vehicle and pedestrian entrances and other minor depressions that do not affect accessibility for firefighting or evacuation.

3.2.2.51. Group C, up to 6 Storeys, Sprinklered

1) A *building* classified as Group C is permitted to conform to Sentence (2), provided

a) it is *sprinklered* throughout,

b) it is not more than 6 *storeys* in *building height*,

c) it has a height not more than 18 m measured between the floor of the *first storey* and the uppermost floor level that does not serve a rooftop enclosure for elevator machinery, a stairway or a *service room* used only for service to the *building*, and

d) it has a *building area* not more than

i) 9 000 m2 if 1 *storey* in *building height*,

ii) 4 500 m2 if 2 *storeys* in *building height*,

iii) 3 000 m2 if 3 *storeys* in *building height*,

iv) 2 250 m2 if 4 *storeys* in *building height*,

v) 1 800 m2 if 5 *storeys* in *building height*, or

vi) 1 500 m2 if 6 *storeys* in *building height*.

When reading the previous sentence, a sharp mind might notice the inaccuracy of this intent. Limiting *building height* by *storeys*, which have no stated or inherent maximum height, leads to arbitrary limits that must be further defined in meters in order to quantify the level of risk (as seen in Section 3.2.2. Building Size and Construction Relative to Occupancy).

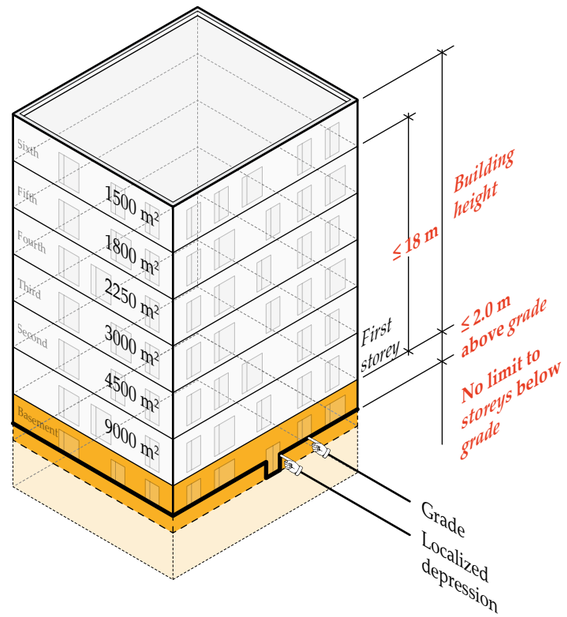
The distinction between measuring *building height* in *storeys* and in meters is also an important one. Measuring in *storeys* (with associated *building area*) limits the net floor area of a building which allows the code to approximate the fire load of contents and partitions.[385] On the other hand, measuring in meters (with associated *building area*) limits the total volumetric risk and dictates the degree of firefighting possible. In the case of 6 storey, sprinklered buildings, despite the identical requirements between *combustible* and *noncombustible construction*, "floor assemblies shall be *fire separations* with a *fire-resistance rating* not less than 1 h", the *combustible* building is limited to 18 m (and ¼ of the *building area*) while the *noncombustible* one has no defined absolute height limit.

Building height is also often used as the threshold at which fire safety regulations change, often creating significant jumps in requirements (rather than scaling linearly), which gives it an outsized impact on prescribing the embodied carbon of a building. Nowhere is this more apparent than in the division of Part 9 from Part 3 (outlined in Article 1.3.3.3.) which has major implications for, among others, fire safety, cost, and professional requirements; all of which have embodied carbon impacts (figure 3.29). Defining these large changes in fire safety requirements through the current definitions, which rely on the apparently arbitrary value of 2 meters above *grade*, undermines the scientific basis of the code. Further, setting a *building height* based on *storeys* disincentives and limits innovative design which might allow for 7 *storeys* to fit within the same absolute height limit as is currently allowed for 6 *storeys*. The current 18 m maximum for article 3.2.2.51. between the first floor and the top floor (floor 6 in this case) assumes a maximum floor-to-floor height of 3.6 m, where the same height might be divided into floor-to-floor heights of 3 m allowing for a total of 7 *storeys*.

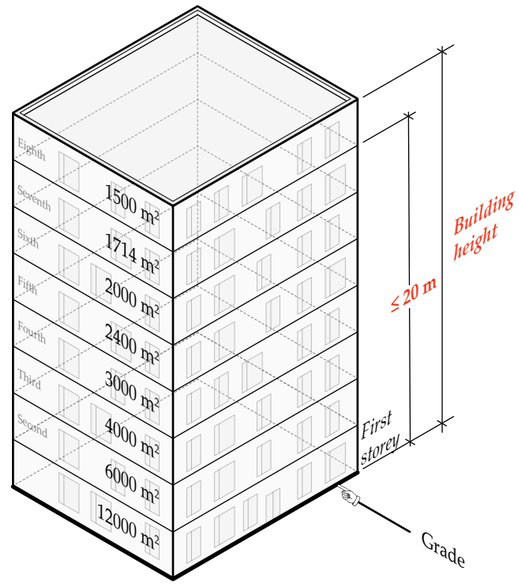
Fire Safety Impact

Undoubtedly, the taller a building is, the greater risk it presents – although the degree to which it increases is not a linear function. The risk that height presented was considered to greatly increase

385. Calder and Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada," 88–95.



a) NBCC 2020 Height Limit of Group C, up to 6 Storeys, Sprinklered



b) Proposed Height Limit of Group C, up to 6 Storeys, Sprinklered

f 3.30

Application of building height defiinition to and Group C, up to 6 Storeys, Sprinklered.

There are no limits to the number of storeys below grade for Part 9 buildings however they are less likely to be built in practice than in Part 3 buildings which may house parking or other uses.

where it exceeded the capability of firefighting services, as noted in the 1931 National Bureau of Standards report, "The height at which construction requirements should become more drastic from a fire-resistance standpoint is determined very largely by the height above which a city fire department can not cope successfully with fire from the exterior of a building because of limitations of water pressure and apparatus."[386]

The caveat to this, is that with the introduction of sprinklers, the traditional practice of exterior firefighting has shifted to an interior approach that recognizes the reliability and effectiveness of sprinkler systems. The change in firefighting access for additional height (up to 18 m above *grade*) therefore, is simply additional flights of stairs, regardless of construction type. Regulating *building height* by *storeys* has no direct fire risk implication as noted by the reports which supported the increase from 4 *storey* to 6 *storey combustible construction*. They indicate that absolute height, not the number of *storeys*, increases risk.[387] [388]

Firefighting approaches do change in taller buildings, as noted by the high building requirements in subsection 3.2.6. which are "intended to maintain safe conditions for occupants of a high building who may have to remain in the building during a fire, and to assist the firefighters by providing efficient access to the fire floor" by controlling smoke movement through the building, particularly through stair, elevator, and other vertical shafts.[389] Interestingly, these additional measures only kick in for Group C (residential) buildings "whose floor level is more than 18m above *grade*." It sets a distance above grade at which evacuation and fire suppression becomes more difficult, and is an understandable limit to set, given that most Canadian ladder trucks will reach between 22.8 m and 30.5 m (75'-100') (figure 3.31).[390] The additional height, a difference of about 5 m, accounts for differences in grade and horizontal distance from the building. Interestingly, the 18 m threshold height value which moves a *combustible* building out of 3.2.2.51. (Group C, up to 6 Storeys, Sprinklered) is measured between the floor level of the *first storey* and floor level of the uppermost *storey*, while the same 18 m height is measured between *grade* and the floor of the uppermost *storey* when considering additional high building requirements. Further research is necessary to quantify the determination of the threshold used in subsection 3.2.6. given its large impacts on firefighting tactics.

While there is a recognition that floors far above *grade* present greater risk, the code does not recognize the same for floors below

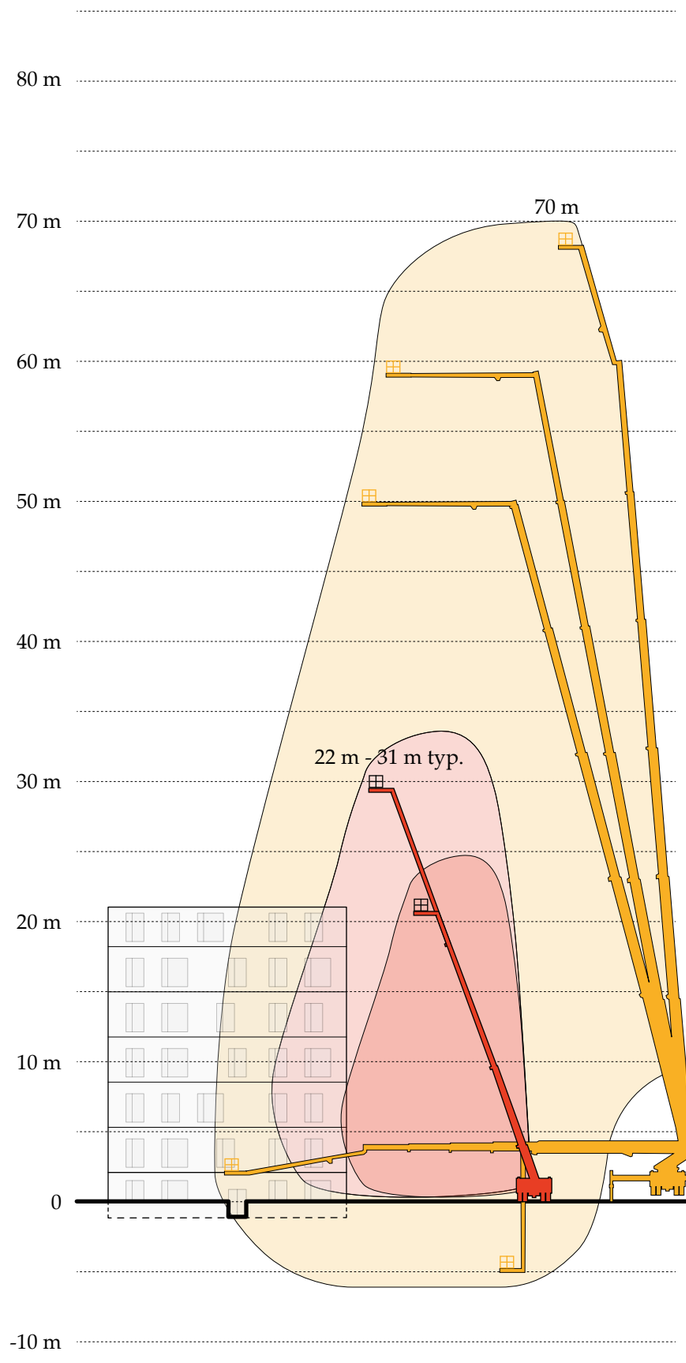
386. U.S. Department of Commerce, Bureau of Standards, Building Code Committee, *Recommended Minimum Requirements for Fire Resistance in Buildings*.

387. GHL Consultants Ltd, "Technical and Process Risks in 5 and 6 Storey Wood-Frame Buildings of Residential Occupancy."

388. Calder and Senez, "Review of Proposed Building Code Changes to Permit 5/6 Storey Wood-Frame Construction."

389. Canadian Commission on Building and Fire Codes, "NBCC 2020," 3-246 Division B.

390. Fire Apparatus & Emergency Equipment Staff, "The Impact of Reach."



f 3.31

Comparison of aerial truck capability with 6 storey building height. Typical aerial capability (red) and new Bronto Skylift (yellow) recently aquired by Toronto Fire Department.

Firefighting capability has increased significantly in recent years through taller aerial trucks. Typical aerials range from 22-31 m in reach, allowing for access above 6 storeys. Regardless, most firefighting occurs from within when the building is less than 6 storeys in height.

grade. Basement apartments are not just less "nice" than above grade units, they are also less safe. From an occupant perspective, they typically present greater risk through decreased opening size for escape in the event of a fire; however, Code enforcement in larger multi-unit buildings largely takes care of this issue. On the other hand, for firefighters, basements present significant, additional risk as a result of necessitating access from above a fire event; increasing the likelihood of firefighters falling through a floor assembly into a burning basement and of being trapped by the rapid onset of hot gasses flowing up from a basement. Voluntary reporting suggests that falling into basements accounts for about 17% of all "mayday" calls between the years 2015 and 2021.[391] Experiments have indicated that the most effective method of firefighting a basement fire may be from the exterior given that fighting a fire is significantly more effective and safer when the firefighter is on the same level as the flame.[392]

The Code further ignores safety below grade by regulating *building area* as a function of *building height* in *storeys* – the current limits seem to have a linear relationship with one another such that all allowable buildings in a category have the same net floor area (e.g. 9000 m² for one *storey* is equal to 4500 m² on two *storeys*), which has long been a tenet of the Code. However, when basement floor area is included, this relationship is no longer true: 9000 m² on two *storeys* (basement and *first storey*) allows for a larger net floor area than 4500 m² on three *storeys* (basement plus two *storeys*). The discounting of below grade floor area incentives low building heights by decreasing the net floor area as buildings increase in height (figure 3.33). Additionally, the definition of *building area* only accounts for "the greatest horizontal area of a *building* above *grade*" which enables below grade storeys to extend greater than the permitted *building area* further rewards below grade construction without accounting for the fire safety risk it presents.

Embodied Carbon Impact

Since *building height* is currently measured from the *first storey*, it is reasonable for a profit-driven developer (or anyone for that matter) to push the *first storey* as far from *grade* as possible in order to fit another floor of occupancy below it. By defining first storey in this manner, it practically legislates that buildings are built with a basement wherever possible, which is significant given

391. Abbott et al., "Project Mayday: A Comprehensive Study of 'Mayday' Incidents, Responses, and Prevention, 2015-2021, 72 Months."

392. Madrzykowski and Weinschenk, "Understanding and Fighting Basement Fires."

that foundations account for up to 42% of a building's embodied carbon emissions on average.[393] While, from an embodied carbon perspective, it may be beneficial to eliminate reinforced concrete wherever possible, this is unlikely given its beneficial properties and embeddedness within the industry. Instead, regulation should look to enable different construction options where possible.

A non-exhaustive review of literature by Feikert and Mueller found that foundations contributed from 7% to 42% of a building's embodied carbon, representing the vast range of geology and foundation types included in the studies.[394] Nonetheless, this data conveys the potential of reducing substructure emissions. Research conducted by Ha/f Studio and University of Toronto students found that between 20% and 66% of embodied emissions were the result of below grade construction in Toronto multi-unit buildings, reflective of both reinforced concrete and the rigid insulation (typically extruded polystyrene). In contrast, they found that in the one building which did not have floor area below ground, only 8% of its embodied emissions were derived from its foundation.[395]

While the substructure of mid- and high-rise buildings varies significantly based on the geology and loading patterns, low-rise housing tends to follow the singular typology of basement foundations in Canada. Concerns about frost heave, necessitated by climate and couched in tradition, have led to the assumption that buildings in Canada must be built on foundations that extend below the frost line in order to prevent upheaval. Frost-protected shallow foundations have been used successfully for more than 60 years, typically using rigid insulation extending laterally and vertically, and are an accepted part of the NBCC.[396] [397] While the risk of differential movement must be more carefully considered, moisture issues, soil pressures, and cost are minimized.

No literature was found that compared basement floor area with the same above floor area, however one study found that while adding a basement increased the overall embodied carbon of a project, it decreased the carbon intensity – as a result of doubling the floor area without a proportionate increase in emissions. The results are expected, given that the single storey comparison also has a foundation, the basement option only adds concrete walls.[398] In order to quantify the impact of the definition of *building height* encouraging below grade construction, a counterfactual LCA based on the Marquette Residences by _naturehumaine in Montreal was completed (figure 3.32).[399] The project, completed in 2015, is

393. Simonen et al., "Embodied Carbon Benchmark Study: LCA for Low Carbon Construction."

394. Feickert and Mueller, "Thin Shell Foundations."

395. Doran, "Why We Need Embodied Carbon Benchmarks and Targets in Building Standards and Policies."

396. Canadian Commission on Building and Fire Codes, "Structural Commentaries (User's Guide)."

397. Buchan Lawton Parent Engineers Ltd, "Insulated Slab-on-Grade Foundations."

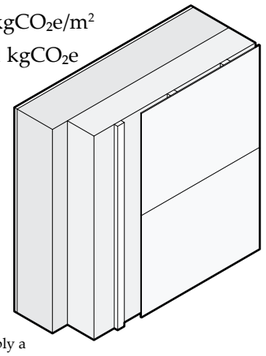
398. Hartmann, özdemir, and Hafner, "What Is the Impact of a Basement on a Building LCA and What Role Does the Functional Unit Play?"

399. _naturehumaine, "Marquette Residences."

Basement storey total: 27,711 kgCO_2e

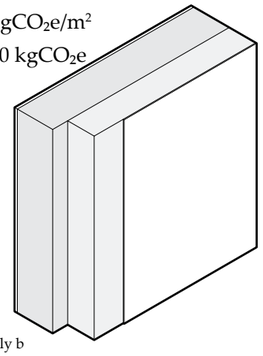
Building total: 72,836 - 117,961 kgCO_2e

206 kgCO_2e/m^2
2,101 kgCO_2e

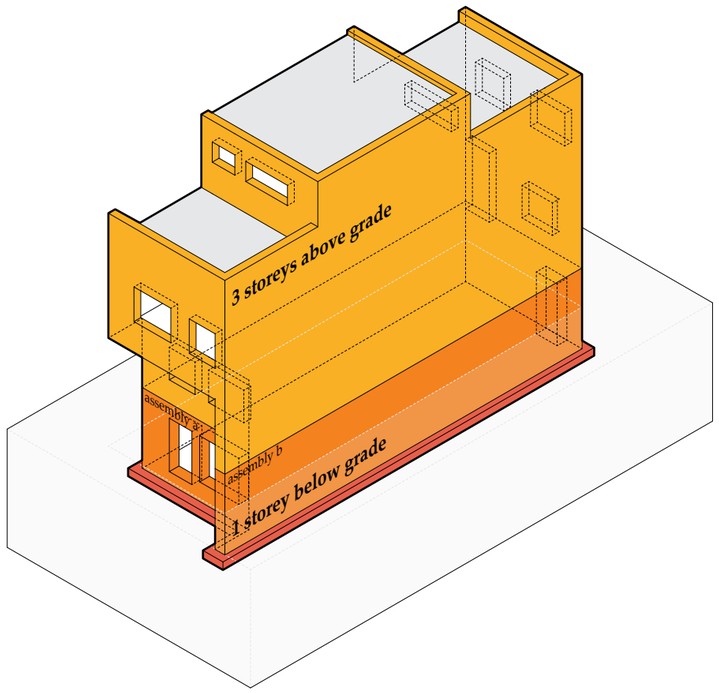


assembly a

181 kgCO_2e/m^2
12,380 kgCO_2e



assembly b



a) Marquette Residences as Built

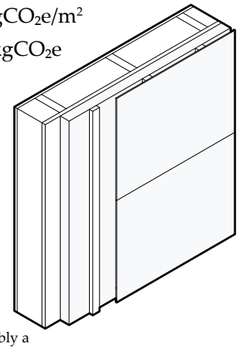
Basement storey total: 17,680 kgCO_2e

Building total: 62,805 - 107,930 kgCO_2e

Difference: 10,031 kgCO_2e

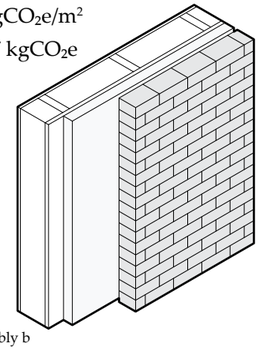
Reduction: 9% - 14%

53 kgCO_2e/m^2
541 kgCO_2e

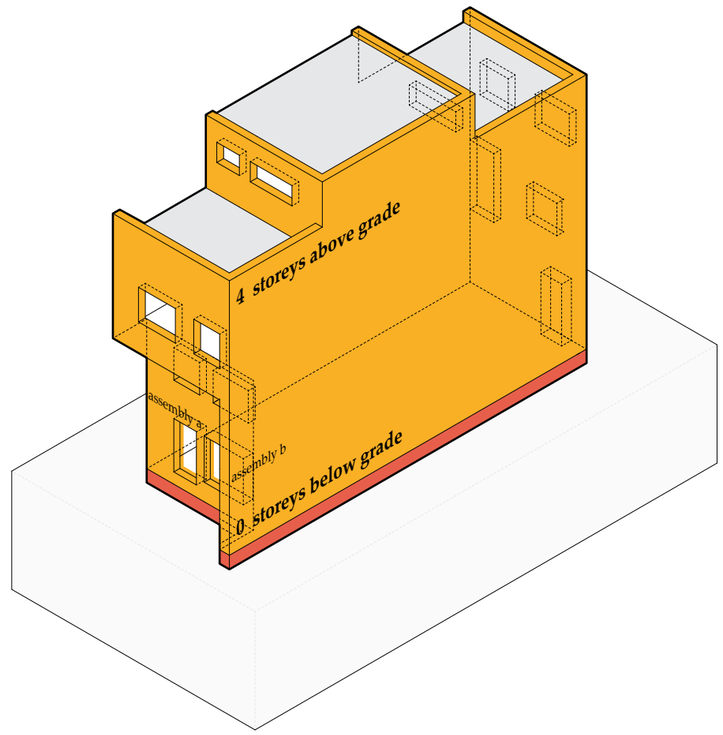


assembly a

83 kgCO_2e/m^2
5,677 kgCO_2e



assembly b



b) Marquette Residences as Possible to Build under Proposed Change

f 3.32

Comparison of the embodied carbon of Marquette Residences as built and under proposed change.

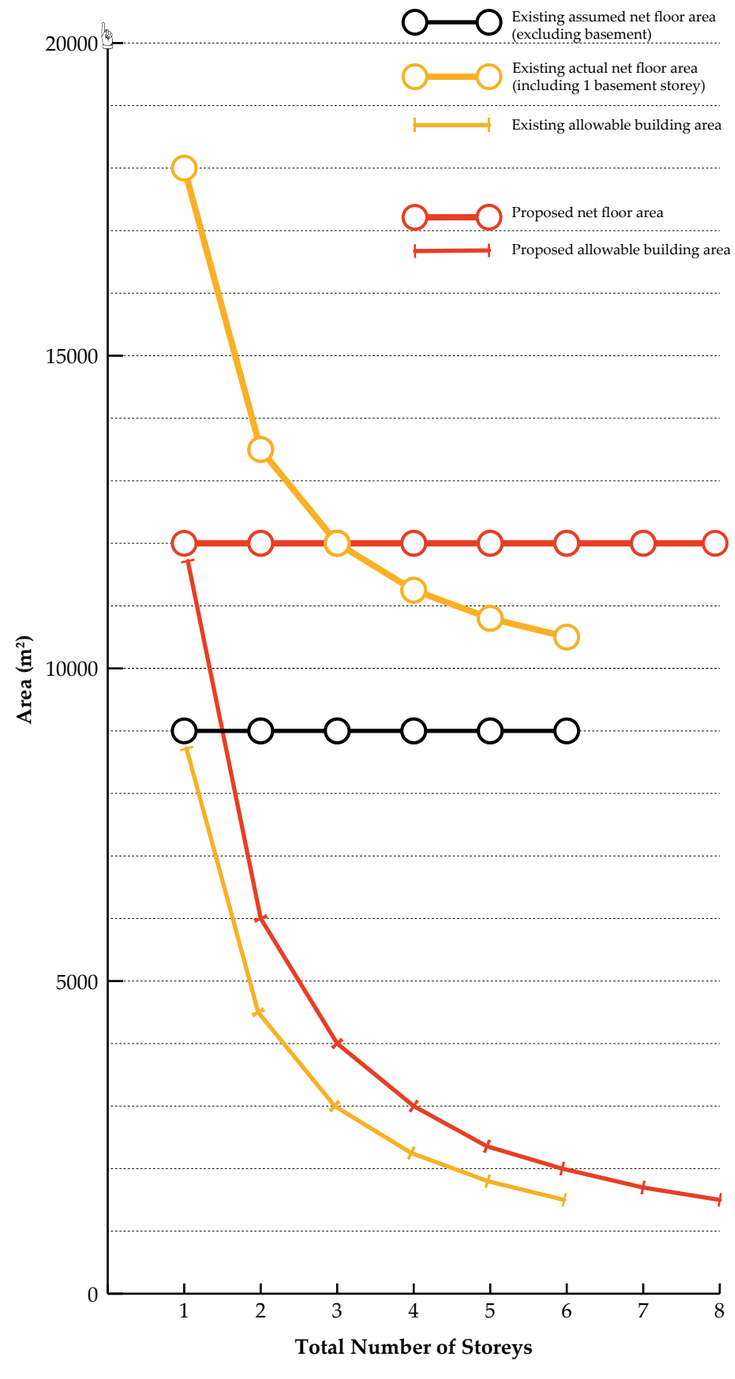
Range of total embodied carbon values assumes that remainder of floor area is between 250-500 kgCO2e/m2. Assemblies are assumed based on drawings and photos by architect and typical details. Design b) uses a frost protected slab on grade. Note that the embodied carbon values presented are strictly for material production and do not include site work or excavation. See appendix for full details.

a straightforward six-unit building with 3 storeys above grade and a basement. The existing project was compared to the same design, lifted approximately 2 m in order to eliminate the basement in favour of a shallow foundation and above grade walls. While acknowledging the limitations of restricting the analysis to only the structure and envelope of a single building, the building uses a mix of framing and cladding materials, as well as significant insulation material which allows it to act as a reasonable example of buildings across the country. While the savings through the reduction of concrete grade beams was modest, significant savings occurred as a result of substituting concrete for wood framed walls. At the project scale, eliminating the basement in favour of another above grade storey reduced the embodied carbon by 9%-14% (assuming between 250-500 $kgCO_2e/m^2$ for the remainder of the floor area), without even accounting for the emissions associated with excavation.

Beyond the practical material changes that would come with changing the definition of *first storey*, there are geometric ones as well. Increasing the number of allowable *storeys* for some building occupancies as outlined in the Proposed Change section, would have a profound impact on the embodied carbon of homes. Comparing a 7 *storey* (allowably defined as 6 *storeys* under current definitions) building to an 8 *storey* (proposed) building of approximately the same net floor area has important geometric qualities which have the potential to lower the embodied carbon of a building. While the surface area to volume ratio is slightly less efficient (0.19 compared to 0.2), it allows for a greater percentage of the floor area to be within 4 m of the exterior wall. This property is critical for developing efficient and dense housing which has the potential to reduce emissions. Further, and of greater importance at an urban scale, the reduced *building area* of the 8 *storey* option enables 19% more bedrooms per m^2 of land area. While in itself, this increased density (per land area) does not impact carbon, it has a multitude of cascading effects as outlined in Barrier #2 such as: reduced infrastructural distances, increased blue/green space, reduced transport requirements, and decreasing housing costs.

Proposed Change

Given that measuring *building height* in *storeys* and meters both come with different quantifiable limits, it is reasonable that both should apply when defining building size and construction relative



f 3.33

Number of storeys, including basements, compared to building/net floor areas of Group C, up to 6 Storeys, Sprinklered.

The black line shows the false assumption of a constant net floor area regardless of the number of storeys. The proposed change would continue the existing relationship between building area and actual net floor area.

to occupancy. Limiting the maximum number of *storeys* above two meters from *grade* is counterintuitive and does not account for the additional fire risk of the storeys below the "*first storey*". The proposed limit of 20 m accounts for the existing limit of 18 m, plus the 2 m distance allowed between the *first storey* and *grade* (figure 3.30). Further, by defining height this way, it encourages development below *grade* in order to accommodate an additional *storey* without moving into the next greatest building size category.

The discrepancy between prescribing a maximum height in meters for *combustible construction* and no maximum height for *noncombustible construction* should be resolved to either list a maximum height for both or neither. Providing a maximum height between first and uppermost floor controls the additional difficulty of fighting fires and evacuating occupants on floors greater than 18m from first storey – considerations which are broadly unrelated to the relative combustibility of the structure. The regulation unfairly imposes a barrier on one type of construction over another, and is more appropriately regulated by Section 3.2.6. Additional Requirements for High Buildings which applies to buildings with floor levels more than 18 m above *grade*.

A third proposed change allows for an additional storey of building height (in addition to the one created by redefining first storey), provided the building area decreases proportionally following the linear scaling already enacted by the code, although whether these reductions are warranted should be further researched.[400] This change would allow for greater flexibility in building form which in turn has the ability to accommodate more bedrooms (and decrease carbon intensity) without increasing the total fire load or risk. In order to remediate these changes, this thesis proposes that:

1. *First storey* is redefined as the *storey* furthest below *grade*, except as permitted by article 3.2.1.2. (Storage Garage Considered as a Separate Building).
2. *Basement* is redefined as any *storey* with its floor level below *grade*.
3. Group C, up to 6 Storeys, Sprinklered and Group C, up to 6 Storeys, Sprinklered, *Noncombustible* Construction, be limited to a height not more than 20 m measured between *grade* and the uppermost floor level that does not serve a rooftop enclosure for elevator machinery, a stairway or a *service room* used only for service to the *building*, and

400. Calder and Senez, "Review of Proposed Building Code Changes to Permit 5/6 Storey Wood-Frame Construction."

4. All *building heights* of Group C occupancies in Section 3.2.2. Building Size and Construction Relative to Occupancy be increased by 2 *storeys* (in order to match the outcome of current regulations and allow for one additional storey provided they fall within the 20 m height limit).
    a. 12,000 m² if 1 *storey* in *building height* (new allowance for a single *storey* without a *basement*),
    b. 6,000 m² if 2 *storeys* in *building height* (currently defined as 1 *storey* building),
    c. 4,000 m² if 3 storeys in building height,
    d. 3,000 m² if 4 storeys in building height,
    e. 2,400 m² if 5 storeys in building height,
    f. 2,000 m² if 6 storeys in building height,
    g. 1,715 m² if 7 *storeys* in *building height* (currently defined as 6 *storey* building),
    h. 1,500 m² if 8 *storeys* in *building height* (new allowance for additional *storey* above current regulations).

Barrier #5:
Timber Building Height

Regulation and Interpretation

Wood buildings represent the majority of the building stock in Canada by the simple fact that low-rise housing types dominate our built landscape.[401] Timber has been the most abundant building resource in Canada; from indigenous buildings to contemporary homes, wood (and primarily small wood members) has been the building material of choice due to its availability, workability, and low cost. The building culture in Canada and the United States is relatively unique and the North American expertise in light wood construction is very well developed. Small, detached and semi-detached housing has proliferated in these land rich, resource rich nations – largely enabled by the development of light wood construction.

As outlined in Part Two, wood frame buildings were the overwhelming majority in 19th century North America, even in large urban centers. After a series of devastating conflagrations, and in concert with developing building technologies, wood construction has fallen out of favour for its perceived lack of safety and heavy restrictions.[402] Up until recently, light wood framing was the only mainstream option for low carbon construction, and its height limitation of not more than 4 storeys severely impeded its inclusion in urban centers. However, in 2015, the NBCC increased the allowable combustible building height from 4 storeys to 6 (and increased allowable area) (figure 3.34), a change that was in the making for nearly 10 years. The change reflected research which showed that the additional floors were not likely to increase the risk associated with any of the NBCC's objective statements, and further, that the additional protections would likely make the new buildings safer than their 4 storey predecessors.[403] [404] In addition, the 2020 NBCC pulled mass timber out of the broad *combustible construction* type and introduced the category of *encapsulated mass timber construction* (EMTC) in order to reflect its inherent fire resistant properties, and enabled its use in construction up to 12 storeys (figure 3.35). British Columbia built upon these limits to allow up to 18 storeys of EMTC in 2024.[405] These Code changes signal a larger shift than

f 3.34

Excerpts from NBCC 2020.

401. Government of Canada, "2021 Census of Population."

402. Ahmed and Arocho, "Identifying the Level of Awareness and Challenges to Adopt Mass Timber by the Construction Practitioners in the United States."

403. Harmsworth et al., "Recommended Building Code Changes to Permit 5 and 6 Storey Wood-Frame Buildings of Residential Occupancy."

404. GHL Consultants Ltd, "Technical and Process Risks in 5 and 6 Storey Wood-Frame Buildings of Residential Occupancy."

405. Ministry of Housing, "British Columbia Building Code."

1.4.1.2. Defined Terms

Noncombustible construction means that type of construction in which a degree of fire safety is attained by the use of *noncombustible* materials for structural members and other *building* assemblies.

Combustible construction means that type of construction that does not meet the requirements for *noncombustible construction* or *encapsulated mass timber construction*.

Encapsulated mass timber construction means that type of construction in which a degree of fire safety is attained by the use of encapsulated mass timber elements with an *encapsulation rating* and minimum dimensions for the structural timber members and other *building* assemblies.

3.2.2.48. Group C, up to 12 storeys, Sprinklered

1) A *building* classified as Group C is permitted to conform to Sentence (2), provided

a) it is *sprinklered* throughout,

b) it is not more than 12 *storeys* in *building height*,

c) it has a height not more than 42 m measured between the floor of the *first storey* and the uppermost floor level that does not serve a rooftop enclosure for elevator machinery, a stairway or a *service room* used only for service to the *building*, and

d) it has a *building area* not more than 6 000 m².

2) Except as provided in Article 3.2.2.16., the building referred to in Sentence (1) is permitted to be of *encapsulated mass timber construction* or *noncombustible construction*, used singly or in combination, and

3.2.2.51. Group C, up to 6 Storeys, Sprinklered

1) A *building* classified as Group C is permitted to conform to Sentence (2), provided

a) it is *sprinklered* throughout,

b) it is not more than 6 *storeys* in *building height*,

c) it has a height not more than 18 m measured between the floor of the *first storey* and the uppermost floor level that does not serve a rooftop enclosure for elevator machinery, a stairway or a *service room* used only for service to the *building*, and

d) it has a *building area* not more than

...

vi) 1 500 m2 if 6 *storeys* in *building height*.

2) *Buildings* referred to in Sentence (1) are permitted to be of *combustible construction* or *noncombustible construction*, used singly or in combination, and

simple allowances. It shows that other factors, largely climate-related, stimulated the political will to reconsider and revise these regulations. Existing limits tend to require significant reasoning to warrant inspection, let alone modification, so the introduction of these changes provides optimism for the future.

Combustible construction is used in the NBCC largely as a proxy for light wood frame construction, which uses small, dimensional lumber as the building structure, often covered by gypsum wall board (GWB) (typically known as drywall) in order to achieve a required fire-resistance rating (FRR). Light wood framing tends to be cheaper and more readily available in Canada than other construction types, and as a result, is used almost exclusively whenever permissible.[406] EMTC on the other hand, although composed of the same material, has significantly different fire properties. When the change was made to include this type, additional requirements were introduced to approximate the risk posed by an identical *noncombustible* building. These include: sprinklering throughout, 2 hour FRR, floor area limits, and all additional high building requirements that are required in buildings above 18m (measured from *first storey* to floor of uppermost *storey*).[407]

While the results of the current NBCC regulations on residential timber building heights are complex and must be taken into consideration with the entire breadth of other regulations and market forces, the direct impacts lie primarily in reduced cost and carbon. A building's structure has little impact on the day-to-day lives of its occupants at an urban or personal scale; levels of sound attenuation, vibration control, air quality, and daylighting can all be achieved by the range of structural systems. From a market perspective, both light wood framing and mass timber construction tend to be faster to build which reduces debt financing and other carrying costs. While light wood construction benefits from reduced material cost, mass timber tends to be 2-6% higher in cost than alternatives though it may have lower life-cycle costs.[408] [409] Further, reduced structural weight saves both money and carbon in the potential for reduced foundations, while prefabrication and stronger supply chains hold enormous potential for lowering the cost and transport emissions of mass timber construction.[410] [411] These savings may be reduced by additional fire safety requirements.[412]

406. Elling and McKeever, "Wood Products and Other Building Materials Used in New Residential Construction in Canada, with Comparison to Previous Studies."

407. Alam, "Encapsulated Mass Timber: A New Construction Type for the 2020 NBC."

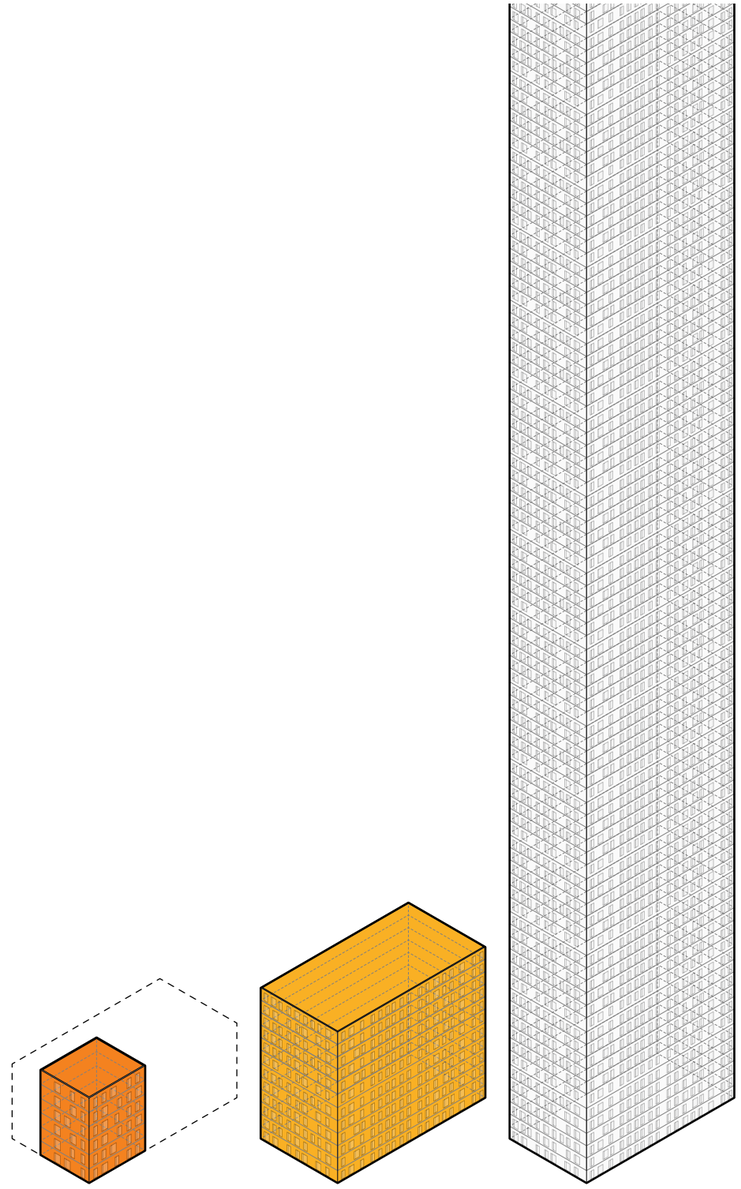
408. Ahmed and Arocho, "Analysis of Cost Comparison and Effects of Change Orders during Construction."

409. Gu, Liang, and Bergman, "Comparison of Building Construction and Life-Cycle Cost for a High-Rise Mass Timber Building with Its Concrete Alternative."

410. Hurmekoski, Jonsson, and Nord, "Context, Drivers, and Future Potential for Wood-Frame Multi-Story Construction in Europe."

411. Scouse et al., "Regional and Net Economic Impacts of High-Rise Mass Timber Construction in Oregon."

412. Bennett and Walker, "Rubber Hits the Road for Six‐Storey Wood‐Frame Construction."

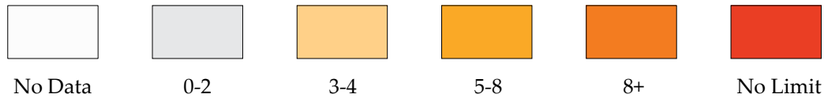


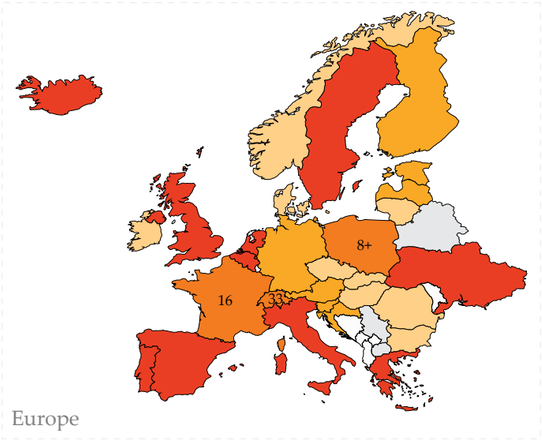
f 3.35

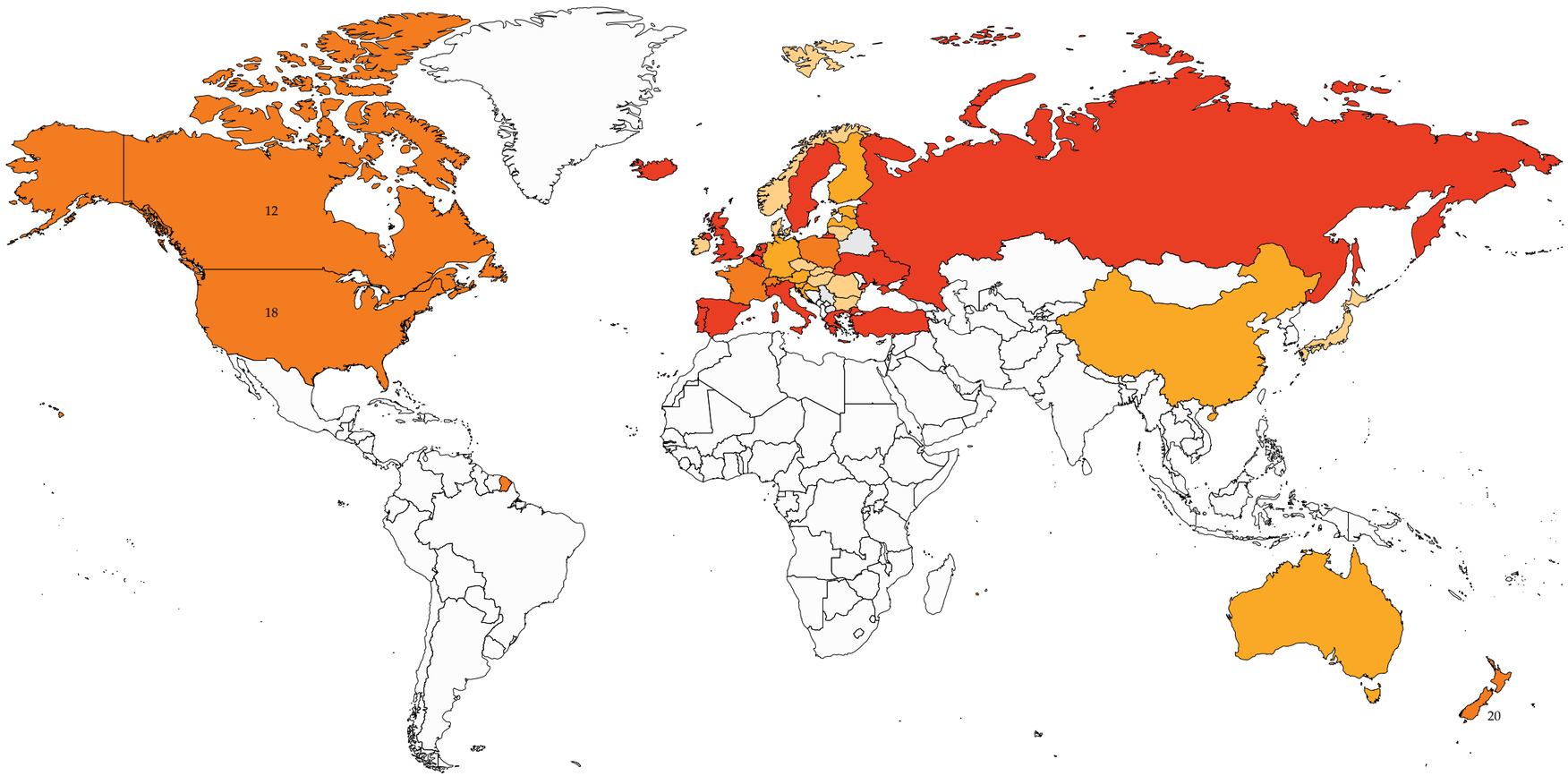
Upper limits of Group C residential building height and building area by permitted construction type.

All upper limits depicted must be sprinklered among other requirements that vary by height and area.

*Noncombustible buildings conforming to the same requirements as 6 storey combustible buildings are permitted to have up to 6000 m² of building area.







f 3.36

Maximum number of storeys with a load-bearing timber structure in sprinklered residential buildings across the world.

Diagram describes the maximum height permitted in prescriptive codes. Timber structure does not distinguish between light wood framing and mass timber. Some storey heights are derived from a maximum height limit. See source document for additional information.

Fire Safety Impact

Inherent in this discussion of maximum timber building height is the implication that *combustible* buildings are more dangerous than *noncombustible* ones. This topic is tackled more directly in Barrier #7; however, this basic assumption is not supported by recent literature. While there are certainly different risks associated with both building types, the decision to separate out these construction types came about as a stepping stone towards a performance-based code in the 1960's which was never realized.[413]

"Noncombustibility is an elemental concept, but 'noncombustible construction' is only a standard that has proved satisfactory for tall buildings and some other situations. When construction using combustible materials is developed that satisfies the conditions, the standard should be changed to permit it… Lacking a satisfactory diagnosis of the problem, responsible authorities place their trust in noncombustibility. Where one can truly eliminate all combustibles there can be no fire… Noncombustibility will always be one, but not necessarily the only, solution."[414]

Further, referring to a building as *noncombustible* is a misnomer, for even within a *noncombustible* building there are significant combustible elements. Interior partitions, blocking in walls, furnishings, and finishes may all be combustible material which contribute significantly to fire growth and propagation, and are largely outside the bounds of the Code to regulate. In testing scenarios, furniture is often substituted for pallets, giving a sense of how readily flammable the contents of our homes are.[415] A study of the combustible content of Canadian multi-family apartments (mostly townhomes) showed that "the average fire load densities in various rooms were estimated to be: kitchens - 807 MJ/m^2; dining rooms - 393 MJ/m^2; living rooms - 412 MJ/m^2; basement living rooms - 288 MJ/m^2; primary bedrooms - 534 MJ/m^2; and, secondary bedrooms - 594 MJ/m^2."[416] Another study, conducted in Turkish high-rise buildings, found that living rooms ranged from 310-379 MJ/m^2, bedrooms from 518-650 MJ/m^2, and kitchens averaged to 552 MJ/m^2.[417] Compare this to an exposed cross-laminated timber (CLT) wall, which presents a fire load of approximately 370 MJ/m^2.[418]

The distinction between *combustible* and *noncombustible* building heights is largely one concerned with the loss of property rather than the loss of life. Combustibility as an inherent material property is involved with contribution to a fire, while FRR encompasses the resistance to ignition and structural integrity under fire conditions.

413. Keith Calder and Peter Senez, "The Historical Development of the Building Size Limits in the National Building Code of Canada" (Sereca Consulting Inc, March 19, 2015), 97-126.

414. Ferguson, "The Problem of '*Noncombustible*.'"

415. Frangi and Fontana, "Fire Performance Of Timber Structures Under Natural Fire Conditions."

416. Bwalya et al., "Survey Results of Combustible Contents and Floor Areas in Canadian Multi-Family Dwellings."

417. Dundar and Selamet, "Fire Load and Fire Growth Characteristics in Modern High-Rise Buildings."

418. Li et al., "Experimental Study of Combustible and *Noncombustible* Construction in a Natural Fire."

Variable	Construction Type		Protection System			
	Combustible	Noncombustible	None	Smoke Alarm	Sprinkler	Both
Fires (n)	7687	311	3061	3132	622	878
Death Rate (per 100 fires)	0.8	1.6	0.8	1.1	0.5	0.6
Injury Rate (per 100 fires)	11.1	10.9	12	12	7.2	11.5
Extinguished by Fire Department	44%	35%	47%	47%	36%	35%
Spread Beyond Room of Origin	20%	14%	30%	15%	18%	11%

f 3.37

Fire severity outcomes in apartment buildings by construction type and protection system in BC, AB, and MN, Canada, 2005–2015 (NFID Dataset).

Confidence intervals can be found in source document.

"Although raw comparisons suggested that fires in apartment buildings constructed from combustible materials showed worse outcomes than those constructed from noncombustible materials, once the protective systems in place were accounted for, the type of construction material was found not to have a significant association with any of the outcomes of interest."

- Zheng et al, 2022

f 3.38

Quote from Alex Zheng, Len Garis, and Ian Pike, "Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and Non-Combustible Construction Materials," 2022.

Tall buildings face additional challenges as a result of their height which should not be understated. From a life safety perspective, taller buildings often have larger occupant loads and greater evacuation times combined with slower response from firefighters due to their location. Despite this, evacuation happens relatively quickly, certainly before the required FRR of 60/120 minutes such that the ignition of a structure should only occur after all occupants have exited the building.[419]

Unsurprisingly, the contribution of an unprotected or inadequately protected wood structure to a fire can be significant. It also tends to change the type of fire, with a faster flashover time and more significant external burning, compared to the ventilation-controlled fires which tend to occur in protected rooms.[420] Despite this, tests have confirmed that sprinkler systems can allow any type of construction to meet fire safety objectives such that "even the damage on the furniture was small." [421] [422] Further, adding an additional layer of gypsum board to encapsulated mass timber construction (for a total of three layers) allows for a total burnout of the fire unit and an encapsulation rating of 130 minutes or greater.[423] [424] The Brock Commons at UBC (18 *storeys*) utilizes this strategy to encapsulate all of its timber elements with three layers of Type X gypsum board.[425] On the global stage, Canada's timber building height limits are relatively average; the 12 storey limit for EMTC is 14th highest out of the 33 countries measured (figure 3.36). However, Canada's height limit relies largely on sprinklers; in buildings without sprinklers, 19 countries allow greater building heights than Canada.[426]

Although from a surface level it would seem that combustible construction would always be less safe than *noncombustible*, passive fire prevention and active fire suppression have almost entirely mitigated the differences between these construction types. Correspondingly, the literature does not support the assumption that *combustible* buildings are inherently less safe. Analysis of real building fires across Canada has shown that the relative combustibility of a structure does not have an effect on fire severity outcomes. Instead, smoke alarms and sprinklers have a much bigger impact on personal safety and suppression (figure 3.37 and 3.38).[427] Modelling has shown similar results, in 6- and 12-storey residential construction, even though temperatures rise more quickly in *combustible* construction than *noncombustible*, light-wood framing and CLT construction types show comparable risk when compared to *noncombustible* construction (see Barrier #7).[428]

419. Proulx, "Evacuation Time and Movement in Apartment Buildings."

420. Li et al., "Experimental Study of Combustible and *Noncombustible* Construction in a Natural Fire."

421. Frangi and Fontana, "Fire Performance Of Timber Structures Under Natural Fire Conditions."

422. Hakkarainen, "Post-Flashover Fires in Light and Heavy Timber Construction Compartments."

423. Hasburgh et al., "Fire Performance of Mass-Timber Encapsulation Methods and the Effect of Encapsulation on Char Rate of Cross-Laminated Timber."

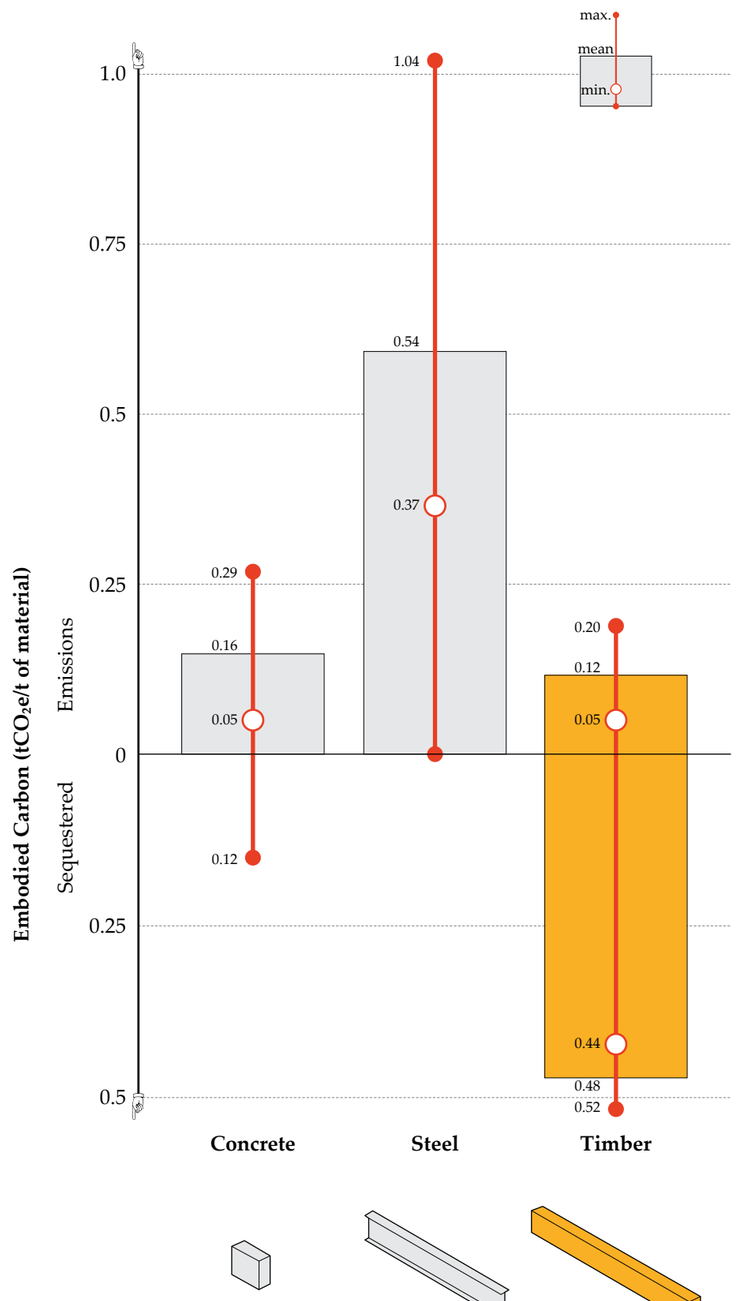
424. Joseph Su et al., "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction," Technical Report (National Research Council of Canada, October 7, 2021), 11, https://nrc-publications.canada.ca/eng/view/object/?id=f444b-1ba-c6f5-49fd-8bd1-d8269c-3717cf.

425. Wood WORKS!, "Brock Commons: A Case Study."

426. Ostman et al., "Fire Safety Requirements in Different Regions."

427. Zheng, Garis, and Pike, "Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and *Noncombustible* Construction Materials."

428. Zhang, Mehaffey, and Hadjisophocleous, "Case Studies of Riskötoölife Due to Fire in Midö and Highörise, Combustible and Nonöcombustible Buildings Using CUrisk."



f 3.39

Embodied Carbon of structural materials by weight.

Note that the concrete value excludes reinforcement which can add a significant amount of embodied carbon.

Embodied Carbon Impact

Undoubtedly, *combustible* buildings tend to be less carbon intensive than those of *noncombustible* material, though the combustibility of a material is not entirely indicative of its embodied carbon. Reducing the embodied carbon of a building's structure relies not on strict material substitutions, but on a relatively straightforward decision-making process of optimizing the efficiency of structural components. Until recently, the structural system of a building has typically been selected by comparing performance, cost, and ease of construction; however, with an expanding understanding of embodied carbon, it too has entered the conversation. While mass timber might be lower carbon (by weight and volume) than steel, a very large span might be more carbon efficient to complete with steel than mass timber given the immense tensile strength of steel.[429] The scope of this section focusses solely on building structure and excludes the knock-on effects that the structural system might have on the carbon intensity of other building components (e.g. framed systems allow for batt insulation while mass systems work better with board insulation).

Although distinct from one another, the majority of embodied carbon from any structural material comes from the extraction and manufacturing phase (A1-A3) (figure 3.39). Light wood frame lumber emits nearly all of its embodied carbon in the A3 manufacturing phase, where logs are debarked, sawn, kiln-dried, and planed.[430] Mass timber products on the other hand, has additional emissions from resins, glues, and further machining to account for, leading to nearly double the carbon (although these emissions come with additional strength and use capabilities).[431] In both cases, the removal of moisture from the timber is the most energy intensive part of the manufacturing process but adoption of high performance drying processes can reduce the associated emissions by up to 48%.[432] Similarly, developing technology in steel production has the potential to reduce emissions by about 80%, although material substitutions will still lead to lower carbon buildings.[433] Concrete, with most of its emissions generated through the production of cement, could potentially reduce emissions by around 50% through the inclusion of low carbon binders and supplementary cementitious materials; these too are in their infancy and have limited application.[434]

Estimates of the reduction potential of wood buildings vary greatly, which represents the complexity of the issue and the degree of caution with which to approach the assumption that wood

429. John Orr, Orlando Gibbons, and Will Arnold, "A Brief Guide to Calculating Embodied Carbon."

430. Canadian Wood Council and American Wood Council, "Environmental Product Declaration: North American Softwood Lumber."

431. Canadian Wood Council and American Wood Council, "Environmental Product Declaration: North American Glue Laminated Timber."

432. Bond and Espinoza, "A Decade of Improved Lumber Drying Technology."

433. Assunööo et al., "Net-Zero Steel in Building and Construction: The Way Forward."

434. Chen et al., "Reducing Embodied Carbon in Concrete Materials."

buildings are the answer to embodied carbon emissions.[435] The embodied carbon impacts of a material change for even a single building present a wide range of values depending on the data and parameters used. Values for the embodied carbon of a given material can vary by a factor of 11.5, highlighting that "any of the most common structural materials could appear to be preferable to the others, if limited and poorly defined calculations are offered for comparison."[436] Nonetheless, attempting to quantify the impact of combustible building systems remains important.

In a systematic literature search and meta-analysis of studies comparing the whole life carbon of mid-rise buildings using varying structural systems, Busby and Himes found that substituting conventional materials in favour of mass timber reduced construction emissions (A1-A5) by nearly 70%. The study examined 11 peer-reviewed articles which contained 18 comparisons, all of which showed that the substitution reduced emissions.[437] Similarly, another systematic literature review (n=95) found that buildings with timber structures have just over 50% of the embodied carbon as buildings with reinforced concrete (figure 3.41).[438] A third review (n=307) suggests that reductions of up to 68% are possible with a wood structural system.[439] The savings from a timber structure are not always enormous, particularly as building size increases; the decision to build a university residence with mass timber reduced emissions by only 19% when compared with a steel frame.[440] A 19% reduction was also found through the replacement of light steel framing with light wood framing.[441] However, a study of a 4 storey multi-unit wood frame residential building in Quebec found that it had just 62% and 78% of the embodied carbon as comparable concrete and steel frame buildings respectively.[442]

Scaling up these reductions brings further complications to the calculation; assuming that mass timber could be substituted for conventional building materials in half of new urban construction *and* that the embodied carbon benefits of mass timber will scale linearly, the material swap could reduce about 10% of global emissions.[443] These are two enormous assumptions with the first relying on global economic shifts, policy changes, and industry growth, while the second requires that the materials harvested will not have harmful carbon effects that offset the benefit (eg. soil carbon storage[444]). The forestry impacts of scaling up the mass timber construction sector will have an impact on the carbon emissions of the resulting building product, although literature does not provide a clear answer.[445]

435. Himes and Busby, "Wood Buildings as a Climate Solution."

436. Moncaster et al., "Why Method Matters."

437. Himes and Busby, "Wood Buildings as a Climate Solution."

438. Chastas et al., "Normalising and Assessing Carbon Emissions in the Building Sector."

439. Minunno et al., "Investigating the Embodied Energy and Carbon of Buildings."

440. Hemmati et al., "Comparison of Embodied Carbon Footprint of a Mass Timber Building Structure with a Steel Equivalent."

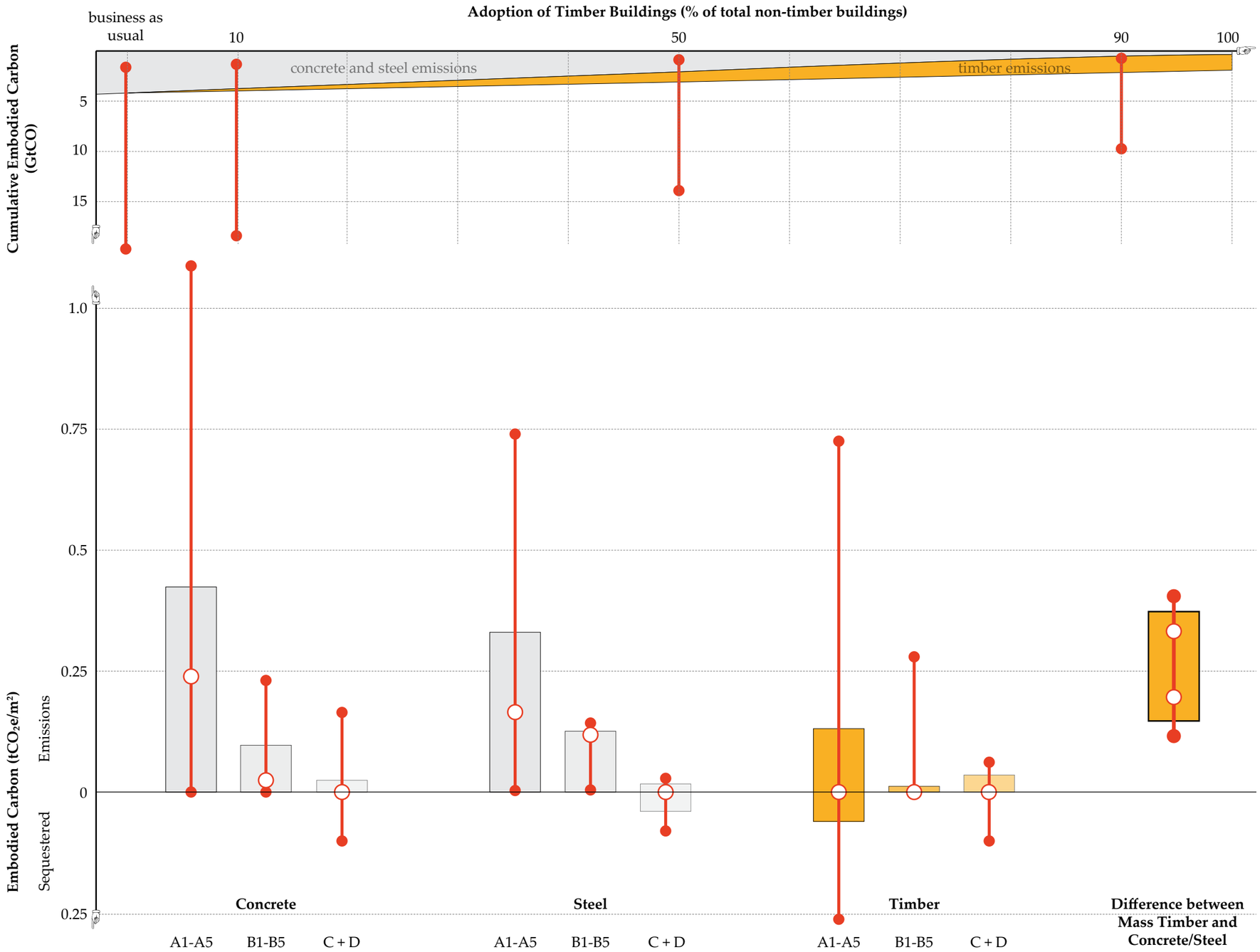
441. Passarelli and Mouton, "Embodied Life Cycle Impacts of Lightweight Building Methods for Affordable Houses in the USA."

442. Padilla-Rivera, Amor, and Blanchet, "Evaluating the Link between Low Carbon Reductions Strategies and Its Performance in the Context of Climate Change."

443. Himes and Busby.

444. Oertel et al., "Greenhouse Gas Emissions from Soils—A Review."

445. Peng et al., "The Carbon Costs of Global Wood Harvests."



f 3.40

Cumulative embodied carbon emissions required for urban construction from 2020-2050 with different adoption scenarios of timber construction.

Significant uncertainty levels exist in the data as a result of unknown floor area per capita and some variability in material emissions.

f 3.41

Embodied carbon of structural systems by material, divided into LCA phases. Extraction, manufacturing, and construction (A1-A5), maintenance and replacement (B1-B5), and end of life (C+D).

Globally, Oliver et al. estimated that a 14%-31% reduction in CO_2 emissions was possible by substituting wood in the place of concrete and steel. These potential savings largely rely on the efficiency of harvested timber, with greater volumes than current practices ending up in building products and the byproducts being used as fuel for timber drying processes.[446] Notably, the study includes global sustainable harvesting limits but states that maximizing forest sequestration is likely incompatible with biodiversity. In another study, Churkina et al. found that if 90% of new builds were designed with timber, we could cut our embodied carbon emissions by approximately 50% (figure 3.40). This study also comes with large variation, indicative of the uncertainty around floor area per capita and material carbon emissions.[447]

It is difficult to estimate the embodied carbon impact of increasing the allowable timber building heights in Canada given the uncertainty around the degree of carbon reduction and the market uptake of this type of construction. Despite this, it is clear that these structures offer the potential for reduced embodied carbon. It is important to remember that while mass timber allows for the lowest embodied carbon structure, efficient and cognizant design decisions can reduce the emissions of steel and concrete structures by 10%.[448] Though there are certainly low- and high-carbon options for the structure of any building, all construction contributes to global emissions and it must be the prerogative of both architects and structural engineers to ensure that any new construction is justified and emissions minimized.

446. Oliver et al., "Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests."

447. Churkina et al., "Buildings as a Global Carbon Sink."

448. Nadoushani and Akbarnezhad, "Comparative Analysis of Embodied Carbon Associated with Alternative Structural Systems."

449. Zheng, Garis, and Pike, "Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and *Noncombustible* Construction Materials."

450. Zhang, Mehaffey, and Hadjisophocleous, "Case Studies of Riskötoölife Due to Fire in Midö and Highörise, Combustible and Nonöcombustible Buildings Using CUrisk."

451. Su et al., "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction."

452. Su et al.

Proposed Change

The NBCC has recognized that *combustible construction* up to 6 *storeys* is acceptable from a fire safety perspective, an allowance of significant importance to embodied carbon. Yet, the combustibility of structural elements remains one of the core tenets of acceptable risk despite that the literature suggests that *combustible* buildings are not inherently more dangerous than *noncombustible* ones,[449] [450] and that high levels of fire resistance are possible with multiple layers of GWB.[451] However, there are significant practical risks (installation, continuity, etc.) which create challenges in ensuring fire safety in a structural system that is readily combustible. While these risks are also present in light steel framing,[452] it seems more reasonable to decrease the limit for this assembly type, rather than increase

the limit for light wood framing. There are other reasons to leave this regulation untouched as well; structurally, light wood frame construction becomes less efficient as you increase the number of storeys which limits its adoption for mid-rise buildings and eliminates it for high-rise structures.[453] From a Code perspective, the 6 storey limit is also the threshold for additional high building requirements, which limits this system's adoption. Further, given the conservatism of the building code document and the practitioners that shape it, a significant amount of time, energy, and resources would be required to demonstrate that increasing the allowable *combustible building height* will not increase fire risk.

From a carbon perspective, the benefit from allowing additional combustible building height is also diminished given the separate regulation for EMTC, which already allows for greater heights with similar embodied carbon intensity. While the effort to increase combustible building heights may not be worth the trouble, EMTC has the potential for greater height and further adoption in residential buildings. Current limits are relatively arbitrary and while more research is needed to further the understanding of EMTC in fire scenarios, current literature suggests that greater heights are safe. Based on the information presented in the Fire Impact section of this chapter, this thesis proposes that:

1. Encapsulated mass timber construction be included as an acceptable solution for 3.2.2.47. Group C, Any Height, Any Area, Sprinklered, provided that:
    a. It is encapsulated with three layers of Type X gypsum board of a thickness not less than 12.7mm (see 3.1.6.6. Encapsulation Materials) when building height exceeds 12 storeys
    b. No exposed surfaces of mass timber are permitted (see 3.1.6.4. Encapsulation of Mass Timber Elements)

"'It must be admitted that by reducing sheer size a hazard may be reduced, but this is also a very crude approach. These hazards could be eliminated if we prohibited the building of buildings."[454]

453. Nadoushani and Akbarnezhad, "Comparative Analysis of Embodied Carbon Associated with Alternative Structural Systems."

454. Advisory Fire Group, Associate Committee on the National Building Code, "Minutes of the Second Meeting of the Panel on Heights and Areas."

Interview with Beth Weckman

D.Eng., M.Eng., P.Eng., Professor (UW), University of Waterloo Fire Research Group Member

Do you have specific examples of places where you think the current testing standards or the current application of those testing standards could be improved to better reflect the actual fire risk?

Can you describe what the difference between flame spread rating, fire resistance rating and combustibility is?

What further research do you think is most pressing?

f 3.42

Excerpts from interview with Beth Weckman on September 5, 2024.

See Appendix A for full transcript.

"Testing standards do not reflect fire risk. Testing standards rank the performance of something - either a system or a material, more often [it's] a material than a system. They are only intended to rank things but... people like to take a number out of a test standard that's intended to rank materials by whatever criteria, most smoke produced to least smoke produced or no smoke produced for example, and [adopt] it as the threshold for design [since] it produces this amount of smoke. But that's not even close, because the smoke from a four-inch piece of material and the smoke in a real fire don't connect… They don't use the right ignition sources, they don't use the right radiative flux, they bear no relation to a real fire scenario unless you're looking at custom design tests."

"Testing standards are intended to derive a relative ranking, but each test method is designed for a particular set of materials. The Steiner Tunnel which measures flame spread rating, is the classic example of this. It is one of the most misused test standards because people keep extending it since it's in the code. You get this vicious cycle where something gets into the code for quite a reasonable purpose and then it gets extrapolated for another purpose [for which it was never intended]. In the case of the Steiner Tunnel, it was designed to mimic the wood coverings at the Coconut Grove nightclub fire. People went to a lot of trouble designing something that gave them the relative ranking, that reflected the fire situation. But then, over time, people have put in pipe sections, they put in loosely held insulation in cages. The test standard must have 29 appendices of different ways of mounting things that should never be mounted for testing in the tunnel in the first place...

Some of those categories are based on full scale performance of the material in practice, but that changes over time because we now have sprinklers, among other measures. If your fire safety system or fire protection measures within the construction industry change over time, then your baseline is a little bit off. And we won't pick up on it necessarily if another safety system kicks in and prevents the fire from doing what it might have in the historical scenario. We don't have a way of separating that out to relate back to the test standard that we might be using to specify in the building code."

"The premise of all of our codes is risk avoidance and minimizing acceptable risk. So here we are, training professionals to minimize risk without learning about how to assess risk. It's hard because there's not really a baseline risk. It's always going be a consensus baseline and we pretty much have to accept that [the baseline] is going to stay a grey area because of public perception and all kinds of other things...

I think it's of paramount importance that we start educating students about [the fundamental parts of the code] - the code can only be as successful as how well the people are educated to apply it. Very few people actually understand what a fire is or what firefighters are facing when they fight a fire. How can you if you don't have any education about fire dynamics? How can you connect a potential deficiency or weak point in the codified version of a design to what might happen? I'm not suggesting anybody is wrong about just applying the code, but we're relying on that code to do an awful lot, when in reality it's pretty specifically defined for square boxes of design from square boxes of information."

Material Scale Barriers

Materials form the basis of the physical world around us, and within architecture, their use is fundamental to the design and composition of buildings. The distribution and use of various materials has traditionally been in response to the properties of that material. As an example, materials that can shed water go on top of the roof while those with high compressive strength hold it up. Applying materials appropriately is essential to a high-performance building, no matter how "high performance" is defined (economically, environmentally, thermally, etc.). Our understanding of materials and their properties, has, for the most part, been reliant on traditional use and experience but as materials increased in availability and complexity, testing was required to empirically determine how a material performs.

Though certainly warranted and useful, testing also has limitations which must not be neglected. In reference to construction materials, the most important are their reductive nature and their determination of values. First, testing only reports on the properties for which the test was designed and is often reductive in its scope, limiting testing to single materials rather than the assemblies that they comprise (e.g. straw bale and plaster coating). Second, tests only determine a materials' properties relative to the performance of other materials.[458] Some characteristics may present specific values and units (eg. perm, °C), while others may be unitless values relative to a baseline (e.g. flame spread rating). Importantly, tests only provide a value which can be interpreted based on the performance of other materials and thresholds within the bounds of the test design.[459] Test results are often extrapolated beyond the original intention of the testing and can contribute to the knowledge gap between actual material properties and perceived properties which is often difficult to contend with. "Not surprisingly, relative to the overall number of materials available for use, architecture uses an extremely limited palette of materials that have been industrially processed and are codified by norms and standards."[460]

The relatively recent integration of carbon metrics into material selection offers an understanding of materials in a more holistic manner through which we may begin to make more thoughtful use of materials. Advances in material development have been the

458. Sadaoui, Dagenais, and Blanchet, "A Comparative Study of Fire Code Classifications of Building Materials."

459. Babrauskas, "Engineering Variables to Replace the Concept of 'Noncombustibility.'"

460. Bechthold and Weaver, "Materials Science and Architecture."

catalyst for a range of historic advances and revolutionary shifts in humanity, but also necessitate new precautions. "It is true that law attempts to provide for safety. The problems arise because the methods of law are not adapted to the application of technological information. The two systems are basically different. Law is arbitrary and precise; it provides the same answer to all questions in any class. Technology recognizes the nature is infinitely variable; it provides a different answer for each situation. Law classifies and regulates real situations, things, entities, whereas technology brings together appropriate functions and is expressed in measurable values. Law deals with arbitrary unique entities. Technology deals with universal abstracts… Using technology, it is necessary only to stipulate values for the characteristics desired and any material that meets these values may be used. Under law, materials must be named. Their characteristics are now known and experience is the only judge as to their suitability for a task. When new materials enter the field, the law not only prohibits them but there is no experience, and protracted delays in their use in building naturally follow."[461]

461. Ferguson, "Building Regulations."

Barrier #6:
Encapsulated Mass Timber

Regulation and Interpretation

When Encapsulated Mass Timber Construction (EMTC) was introduced into the NBCC, the intention was to "develop a set of provisions that achieves the current level of fire safety when wood structural elements are substituted for structural elements of *noncombustible* materials."[462] In order to meet this requirement (or more precisely, approximate the requirement), all EMTC must meet two primary provisions: a minimum *encapsulation rating* of 50 minutes and a minimum dimension for structural elements (96mm for wall, floor, and roof assemblies, see Table 3.1.18.3.) (figure 3.43). The encapsulation rating is intended to delay the addition of mass timber to a fire, while the minimum dimensions are intended to ensure that the structural element exhibits the fire performance characteristics of a large, solid piece of timber, primarily ignition propensity and rate of fire contribution.[463]

While most of the mass timber structure is required to be encapsulated, the Code makes allowances for a select portion to be exempted from encapsulation ratings provided they comply with one of the scenarios outlined in Sentences 3.1.6.4.(3) through 3.1.6.4.(6) (figure 3.44). In 2018, prior to the publishing of the NBCC 2020, the Canadian Wood Council proposed that percent of exposed ceiling in 3.1.6.4.(6)(b) be increased to 100%, which was not accepted.[464] While the limits seem like a relatively small concession to make in favour of acceptably low fire risk, as with all things, the devil is in the details. Particularly at this moment in the Canadian construction industry, the decision to build in EMTC is not taken lightly. It requires more coordination, design expertise, smaller tolerances for error, and is often more expensive than business as usual.[465] Clients often choose this material for its environmental and aesthetic value; encapsulation hinders the first and obfuscates the second.

Encapsulation materials are described in Article 3.1.6.6. and provide two acceptable manners of protection: 38 mm of concrete topping (typically used for floors) and two layers of 12.7 mm Type X gypsum

f 3.43

Excerpts from NBCC 2020.

462. Alam, "Encapsulated Mass Timber: A New Construction Type for the 2020 NBC."

463. Hasburgh et al., "Fire Performance of Mass-Timber Encapsulation Methods and the Effect of Encapsulation on Char Rate of Cross-Laminated Timber."

464. Alam, "Encapsulated Mass Timber: A New Construction Type for the 2020 NBC."

465. Gosselin et al., "Main Motivations and Barriers for Using Wood in Multi-Story and Non-Residential Construction Projects."

1.4.1.2. Defined Terms

Encapsulated mass timber construction means that type of construction in which a degree of fire safety is attained by the use of encapsulated mass timber elements with an *encapsulation rating* and minimum dimensions for structural members and other *building* assemblies.

Encapsulation rating means the time in minutes that a material or assembly of materials will delay the ignition and combustion of encapsulated mass timber elements when it is exposed to fire under specified conditions of test and performance criteria, or as otherwise prescribed by this Code.

3.1.6.4. Encapsulation of Mass Timber Elements

3) Except as provided in Sentence (5), the exposed surfaces of mass timber beams, columns and arches within a *suite* or *fire compartment* need not be protected in accordance with Sentence (1), provided

a) their aggregate surface area does not exceed 10% of the total wall area of the perimeter of the *suite* or *fire compartment* in which they are located, and

b) the *flame-spread rating* on any exposed surface is not more than 150. (See Note A-3.1.6.4.(3) to (6).)

4) Except as provided in Sentences (5) and (6), the exposed surfaces of mass timber walls within a *suite* need not be protected in accordance with Sentence (1), provided

a) each exposed surface faces the same direction, and

b) the *flame-spread rating* on any exposed surface is not more than 150. (See Notes A-3.1.6.4.(4) and A-3.1.6.4.(3) to (6).)

5) The aggregate exposed surface area of mass timber elements within a *suite* permitted in Sentences (3) and (4) shall not exceed 35% of the total wall area of the perimeter of the *suite*. (See Note A-3.1.6.4.(3) to (6).)

6) The exposed surfaces of mass timber ceilings within a *suite* need not be protected in accordance with Sentence (1), provided their aggregate area does not exceed

a) 10% of the total ceiling area of the *suite*, where the exposed surfaces have a *flame-spread rating* not more than 150, or

b) 25% of the total ceiling area of the *suite*, where

i) the *suite* contains no mass timber walls with exposed surfaces, and

ii) the exposed surfaces of the mass timber ceiling have a *flame-spread rating* not more than 75. (See Note A-3.1.6.4.(3) to (6).)

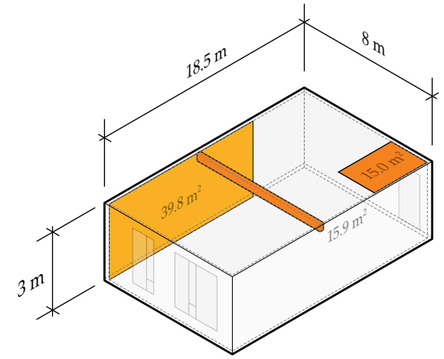
wall board (GWB; typically used for walls and ceilings). It is important to note that the encapsulation rating of an EMTC building is distinct from its required FRR, and does not scale with *building height* as is the case with requirements in both *combustible* and *noncombustible construction*. All residential mass timber buildings fall into 3.2.2.48. Group C, up to 12 storeys, Sprinklered which stipulates a FRR of not less than 2 hours. Note A-3.1.6.4.(3) to (6) explains that all mass timber elements must meet this requirement, regardless of whether they are encapsulated or not. Typically, the fire-resistance of a mass timber element is increased by protecting the element with GWB; CSA O86 notes this contribution as follows:[466]

1. 15 minutes for one layer of 12.7 mm Type X GWB
2. 30 minutes for one layer of 15.9 mm Type X GWB
3. 60 minutes for two layers of 15.9 mm Type X GWB
4. 60 minutes for two layers of 12.7 mm Type X GWB directly attached to CLT

The acceptable encapsulation assembly of two layers of 12.7 mm Type X GWB provides 60 minutes of FRR, which leaves 60 minutes to be accounted for in the depth of the timber element. The depth required for fire-resistance of a structural mass timber element is calculated by multiplying the char rate (65 mm/minute) by the number of minutes of FRR. In addition to this, a zero-strength layer of 7 mm must be incorporated, such that all structural mass timber elements must be oversized by a minimum of 46 mm (60 min * 0.65 mm/min = 39 mm of charring, plus 7 mm of zero-strength), unless otherwise protected (figure 3.46).

The existing NBCC regulations were developed primarily through two studies completed in 2018 by the NRC.[467] [468] In both studies, compartments of mass timber with exposed surfaces were tested without sprinklers or firefighter intervention with similar results. It was found that three layers of GWB completely prevented the ignition and involvement of the mass timber elements in a fire. While in scenarios with 100% exposed ceilings and significant wall/column exposure, different results occurred between the studies: in one, the compartment burned out and self-extinguished,[469] while in the other, the ceiling continued to burn significantly enough to cause it to collapse.[470] It is worthwhile to note that both tests used much more exposed mass timber (and importantly, a combination of ceiling and wall exposure) than the NBCC currently permits. On the whole, Canada's upper limit on timber buildings (both

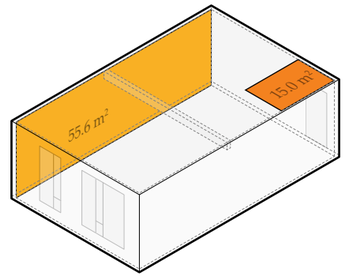
466. Just et al., "Load-Bearing Timber Structures."
467. Su et al., "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction."
468. Su et al., "Fire Safety Challenges of Tall Wood Buildings - CLT Compartment Fire Tests."
469. Su et al., "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction."
470. Su et al., "Fire Safety Challenges of Tall Wood Buildings - CLT Compartment Fire Tests," 2.



Beams & Columns	10%
Walls	25%
Ceiling	10%

*Flame Spread Rating ≤ 150

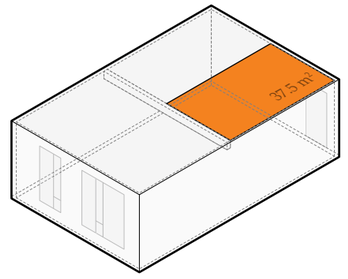
a) NBCC combination 1



Beams & Columns	0%
Walls	35%
Ceiling	10%

*Flame Spread Rating ≤ 150

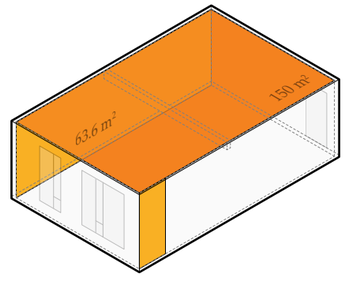
b) NBCC combination 2



Beams & Columns	0%
Walls	0%
Ceiling	25%

*Flame Spread Rating ≤ 75

c) NBCC combination 3



Beams & Columns	N/A
Walls	40%
Ceiling	100%

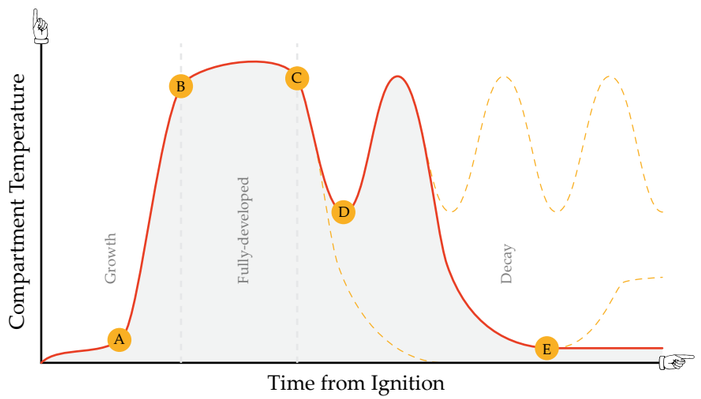
*Flame Spread Rating ≤ 200

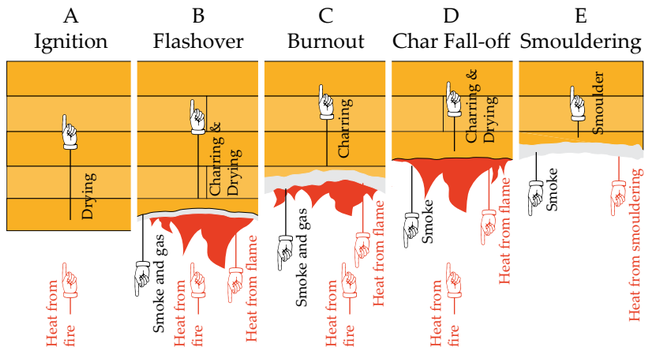
d) IBC Type IV-B maximum exposed surface

f 3.44

Acceptable combinations of maximum exposed mass timber elements in the NBCC and IBC for residential uses.

All scenarios (including the IBC) must be sprinklered. The IBC combination refers to Type IV-C construction which is limited to 8 storeys compared to the 12 storeys permitted in the NBCC examples. The FSR of the timber used in mass timber elements ranges between 35 and 70.

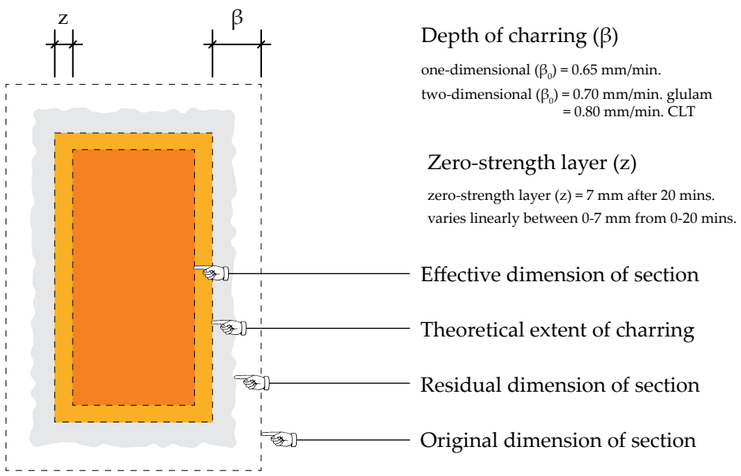




f 3.45

Acceptable combinations of maximum exposed mass timber elements in the NBCC and IBC for residential uses.

All scenarios (including the IBC) must be sprinklered. The IBC combination refers to Type IV-C construction which is limited to 8 storeys compared to the 12 storeys permitted in the NBCC examples. The FSR of the timber used in mass timber elements ranges between 35 and 70.



f 3.46

Loss of section in mass timber elements as a result of charring.

sprinklered and unsprinklered) is fairly high relative to other countries (maximum heights vary significantly from 2 storeys to 33 storeys internationally).[471] [472] Despite this, the Code's encapsulation requirements are more onerous than required elsewhere and mandate that a specific material is used – to the detriment of embodied carbon.

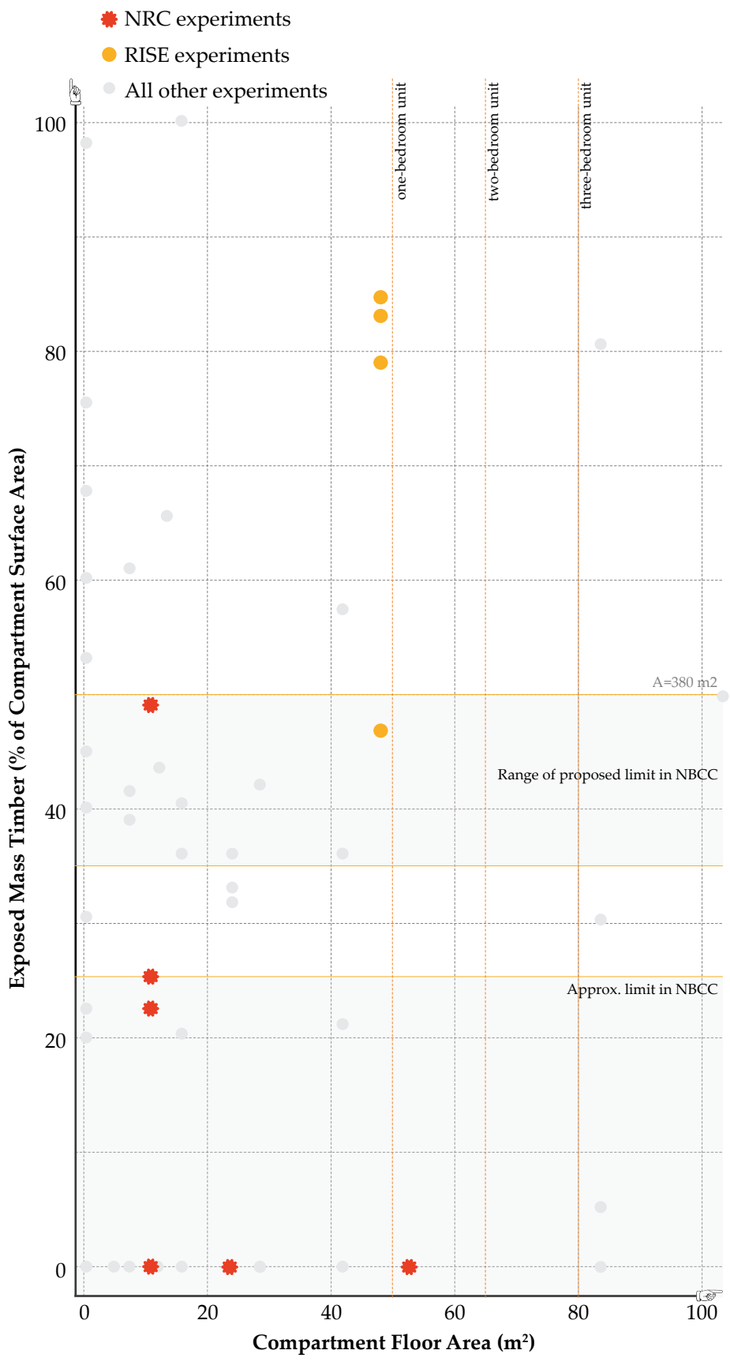
Fire Safety Impact

The fire safety of mass timber buildings is complex and only partially understood given its relative newness. While there is little consensus around the full-scale fire dynamics of mass timber buildings, extensive testing has been conducted and is ongoing to improve our understanding of fire performance. The response of a mass timber element is dependent on many parameters such as physical properties (moisture, density, grain orientation, etc.), thickness, adhesive type, protection, fire intensity, and ventilation.[473] [474] There are a number of considerations identified by previous literature reviews and meta-reviews which must be further researched. The most pressing of these include: the contribution of mass timber elements to heat release rate (HRR), fire spread to exterior and multiple floors, the role of sprinklers, and large-scale compartments.[475] [476] [477] [478] While summarizing the full extent of current research is beyond the scope of this thesis, the limitations of contemporary studies are important to keep in mind.

One of the key differences between mass timber and other construction types is that it undergoes the process of charring in a fire event – an intricate process which slows the contribution of the mass timber element to the fire (figure 3.45). It is a crucial part of understanding the fire resistance and structural capacity of a mass timber element, which has broad implications for the fire unit and entire structure. Charring begins when the temperature of the wood surface reaches 300°C (when protected from flaming or not). This adds to the fuel load and reduces structural capacity which must be accounted for in regulatory considerations. While char can lead to self-extinguishment (although continued smouldering behind GWB requires further research), it can also delaminate in a process known as char fall-off leading to reignition (although improved adhesives have effectively eliminated this likelihood).[479] [480]

A charring model was added to the Canadian design standard CSA O86 in 2014 (currently O86:19) to calculate the structural fire

471. Ostman et al., "Fire Safety Requirements in Different Regions."
472. Ostman, "National Fire Regulations for the Use of Wood in Buildings – Worldwide Review 2020."
473. Kontis et al., "Fire Performance of CLT Members."
474. Mitchell et al., "Review of Fire Experiments in Mass Timber Compartments."
475. Mitchell et al.
476. Buchanan et al., "Fire Safety in Timber Buildings."
477. Su et al., "Fire Safety Challenges of Tall Wood Buildings - CLT Compartment Fire Tests."
478. Liu and Fischer, "Review of Large-Scale CLT Compartment Fire Tests."
479. Mitchell et al., "Review of Fire Experiments in Mass Timber Compartments."
480. Buchanan et al., "Fire Safety in Timber Buildings."



f 3.47

Overview of current research comparing compartment area and exposed surface area.

Further research is needed in large scale compartments as might be found in office spaces or family-sized residential units. Refer to source for further information relating the compartment test to research paper.

resistance of large timber elements. The standard provides rates for one-dimensional and two-dimensional charring and is based on European methods. One-dimensional charring is rated at 0.65 mm/min, which may be a conservative value based on literature (0.63 mm/min) but is in line with Eurocode 5 (0.65 mm/min) and the United States standard (0.64 mm/min) (figure 3.46).[481] Comparison of charring rates for exposed ceilings are consistently lower than that of exposed walls; an average of 16% slower than their wall counterparts, perhaps as a result of smoke accumulation lowering oxygen content.[482] While timber ceilings may burn more slowly than walls, they also create risk for flame spread given that they often span an entire compartment.

In 2021, the International Building Code (IBC; the primary US model code) included three new construction types (IV-A, IV-B, IV-C) that allow mass timber construction in buildings of 18, 12, and 9 storeys respectively (if sprinklered). When introduced, type IV-A buildings had to be fully encapsulated, IV-B permitted 20% of ceilings and 40% of walls to be exposed, and IV-C permitted full exposure. Both type IV-B and IV-C require the same 2 hour FRR as the NBCC.[483] A collaboration between the American Wood Council and the Research Institutes of Sweden (RISE) beginning in 2019 aimed to evaluate the fire safety of exposed mass timber based on updated CLT material standards. One of the key motivators was the aesthetic appeal of exposed timber and the market differentiation that it creates compared to traditional dropped ceilings (figure 3.47).[484] The tests revealed that increasing the allowable exposed area from 20% to 100% can be "implemented while still achieving the performance objectives specified", and were subsequently adopted into the IBC 2024. Notably, the research also presented evidence that a higher percentage of exposed wall area would be justified, though code change leaves the limit at 40% "for the sake of conservatism."[485][486]

Encapsulation refers to the protection of a *combustible* element in order to prevent charring or ignition during the standard design fire. This ensures the structural capacity of the timber member throughout the fire and limits any contribution to the fuel load.[487] FRR on the other hand, is the time that a material will withstand fire as determined by the test CAN/ULC-S101-14 Standard Method of Fire Endurance Tests of Building Construction and Materials (equivalent to ASTM E119 and ISO 834). This test measures the performance of a building element based on a standardized time/temperature curve which research suggests is significantly different than the actual fire conditions a material or assembly might face.[488]

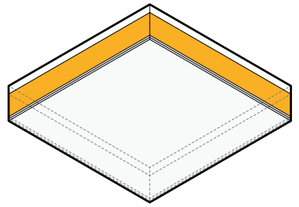
481. Just et al., "Load-Bearing Timber Structures."
482. Gorska, Hidalgo, and Torero, "Fire Dynamics in Mass Timber Compartments."
483. "2021 International Building Code."
484. McLain, "Exposure Allowances in the 2024 IBC."
485. Jones, DiGiovanni, and Baldassarra, "Code Change Proposal: G147-21."
486. Brandon et al., "Fire Safe Implementation of Visible Mass Timber in Tall Buildings – Compartment Fire Testing."
487. Buchanan et al., "Fire Safety in Timber Buildings."
488. Park and Lee, "Fire Resistance of Light-Framed Wood Floors Exposed to Real and Standard Fire."

[489][490][491] The standard furnace test may underestimate the severity of real fires, and thus the fire properties of building materials may be overstated. Peak heat release rates, maximum temperature and duration, and time to failure may all be substantially different under real fire scenarios and require future research (figure 3.47).[492][493][494][495]

Embodied Carbon Impact

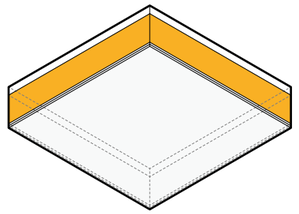
While mass timber construction has the potential to reduce structural embodied carbon emissions by a significant factor, as covered in Barrier #5, the focus of this Barrier is on the impact of encapsulation. Gypsum wall board (GWB), commonly known as drywall, is a sheet material composed of calcinated gypsum mixed with water and additives, faced by paper. While this product has fire-resistive qualities, when exposed to high heat for extended periods of time, it dehydrates and cracks. Type X GWB, specified by the NBCC as both an encapsulation material and fire-resistive one, uses glass fibers to reinforce the core of the panel to reduce cracking and shrinking.[496] While GWB can be recycled, only 10% of its embodied carbon is a result of its raw materials, and 80% is the result of manufacturing.[497] GWB is not the only embodied carbon consideration to account for; even if all encapsulation requirements were removed from EMTC, it would still need to meet a 2 h FRR, which might be reached through oversizing the structural member, applying GWB, or some other product. While there are EPDs available for Type X GWB, no comparison was found to evaluate the carbon efficiency of various materials providing an FRR. The embodied carbon of various floor assemblies of the same 120 minute FRR (with and without an encapsulation rating) were evaluated to determine whether GWB offers a less carbon intensive option than oversizing the timber member (see Appendix B). The comparison considers typical structural requirements (residential loading of 1.9 kPa with 1.5 kPa of concrete topping and a one-way span of 6 m) as well as functional requirements (smooth, deadened floor above). While aesthetic considerations were left out of this comparison, they represent very real additions to all embodied carbon calculations in practice. In this case, it is reasonable to say that only the hollow core concrete slab would be considered to require an interior finish (one layer of non-rated GWB would add approximately 6 $kgCO_2e/m^2$). Given the relatively short replacement cycle of gypsum, a time scale of 60 years was used.

489. Li et al., "Experimental Study of Combustible and Non-Combustible Construction in a Natural Fire."
490. Park and Lee, "Fire Resistance of Light-Framed Wood Floors Exposed to Real and Standard Fire."
491. Li et al., "Experimental Study of Combustible and Non-Combustible Construction in a Natural Fire."
492. Manzello et al., "Real Fire Performance of Partition Assemblies."
493. Manzello et al., "Influence of Gypsum Board Type (X or C) on Real Fire Performance of Partition Assemblies."
494. Lennon and Moore, "The Natural Fire Safety Concept—Full-Scale Tests at Cardington."
495. Jones, "Performance of Gypsum Plasterboard Assemblies Exposed to Real Building Fires."
496. USG Team, "Type X vs. Type C: What's the Difference?"
497. Perkins and Will, "Embodied Carbon and Material Health in Gypsum Drywall and Flooring."



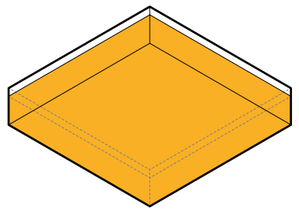
50 mm Concrete Topping
139 mm CLT (5-ply)
60 min. FRR (102 mm residual)
12.7 mm Type X Gypsum Board
12.7 mm Type X Gypsum Board
60 min. FRR (two layers)

a) Assembly A: Encapsulated CLT



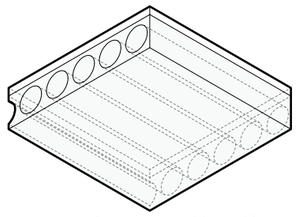
50 mm Concrete Topping
175 mm CLT (5-ply)
60 min. FRR (138 mm residual)
12.7 mm Type X Gypsum Board
12.7 mm Type X Gypsum Board
60 min. FRR (two layers)

b) Assembly B: Encapsulated CLT



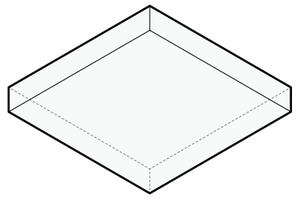
50 mm Concrete Topping
175 mm CLT (5-ply)
120 min. FRR (101 mm residual)

c) Assembly C: Exposed CLT



50 mm Concrete Topping
200 mm Hollow-Core Concrete
Noncombustible

d) Assembly D: Hollow-Core Concrete



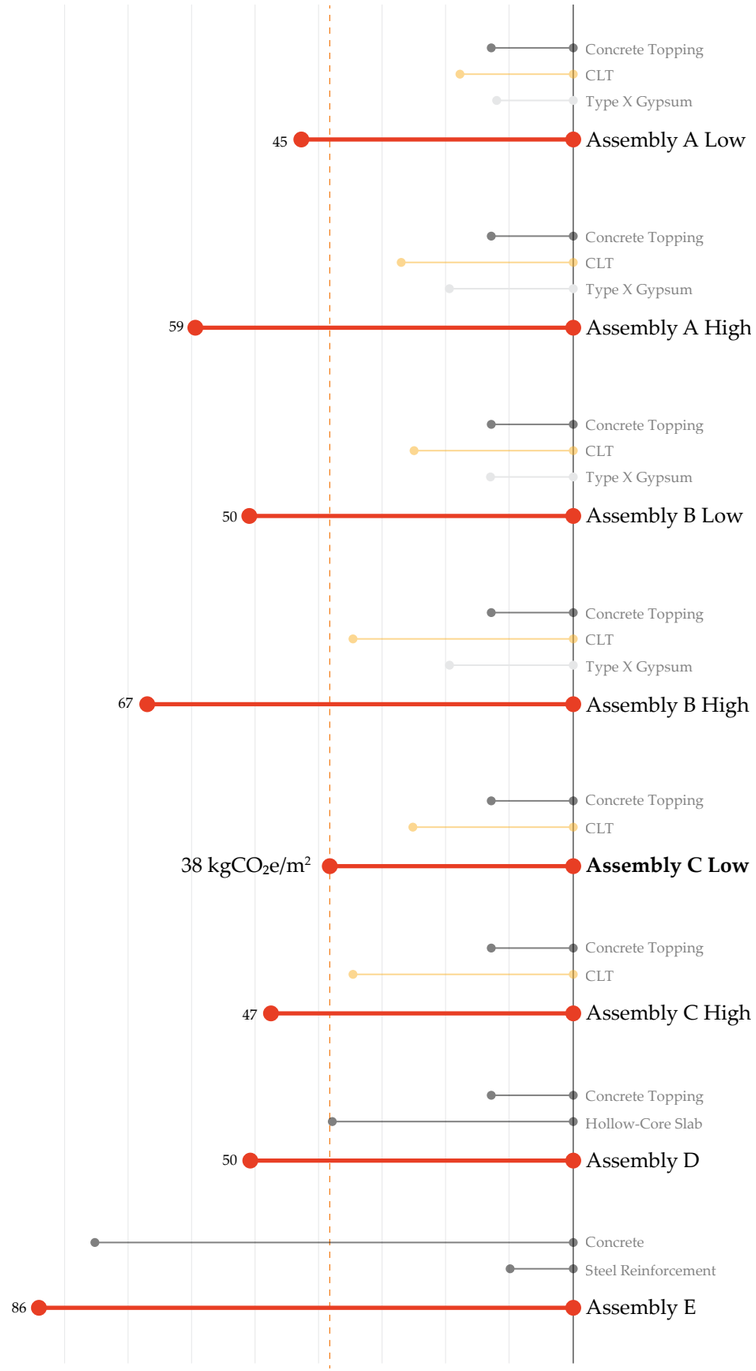
150 mm Cast-in-Place Concrete
Noncombustible

e) Assembly E: Cast-in-Place Concrete

f 3.48

Typical EMTC and noncombustible alternative mulit-unit residential floor assemblies.

The assemblies are all designed to support residential loading (1.9 kPa) and a 50 mm concrete topping (1.5 kPa) at a 6.0 m span. Additionally, they all have a 120 min. FRR regardless of encapsulation.



f 3.49

Embodied carbon of typical EMTC and noncombustible alternative mulit-unit residential floor assemblies.

The embodied carbon of the assemblies does not account for any membranes, fasteners, connections, other auxillery products, or floor finishes.

Five assemblies were evaluated: two of encapsulated cross laminated timber (CLT), one of exposed CLT, and two of concrete. Figure 3.48 outlines the floor assemblies where assemblies A and B represent the typical EMTC (although 139 mm deep CLT panels are significantly less common), assembly C represents the proposed exposed mass timber construction, and assemblies D and E represent typical *noncombustible* alternatives to EMTC (although shallower hollow core concrete slabs may be able to span the same distance, the most common floor element used is 205 mm deep).[498] Given the range of embodied carbon emissions for the CLT and GWB (as a result of different sourcing or manufacturing processes), assemblies A, B, and C, are all calculated with "high" and "low" values to provide a more comprehensive picture.

The results of this study indicate a number of things: most importantly, exposed CLT (C-Low) is the lowest carbon option of the floor assemblies reviewed by 16%-55% assuming that sourcing decisions are consistent (figure 3.49). The 5-ply CLT slab provides a char depth of 74 mm for a 2 hour fire resistance period, leaving adequate depth to retain the 6 m span.[499] Even if higher carbon options are sourced for the exposed CLT (C-High), only A-Low provides a lower carbon option as a result of its reduced CLT thickness. The 139 mm panel in assembly A is composed of 5 layers with two perpendicular layers of 17 mm and three parallel layers of 35 mm, optimizing the depth to achieve typical spans with a 1 hour FRR. This configuration is not available from all suppliers, and as a result, would come with a cost premium.[500] [501] Assembly B, the most likely candidate for EMTC in line with current regulations, is the second highest carbon option, only exceeded by cast-in-place concrete. Even with low carbon sourcing, B-Low emits approximately the same amount of carbon as an average hollow-core concrete slab (assembly D).

This carbon intensity relationship does not scale linearly to a unit or building as the result of ceiling finishes in closets, kitchen cabinets, or bathrooms, which might benefit from a drywall soffit. Assuming 80% of the total ceiling is exposed CLT, the decision would save approximately 480 $kgCO_2e$ for a one-bedroom apartment (assuming a 50 m^2 unit), which translates to approximately 2.4% of a project's total embodied carbon (assuming a baseline intensity of 400 $kgCO_2e/m^2$) as compared to the B-Low scenario required by the NBCC currently. While eliminating 2.4% of a project's embodied carbon is nothing to scoff at, it is not exceedingly large either.

The potential impact of this barrier is largely in its physical value – 10% of current decisions to build EMTC are based on aesthetics even

498. "Precast Solutions - Hollow Core."
499. Structurlam, "Cross Laminated Timber Design Guide."
500. "CLT Specifier Guide."
501. "CLT Specifications and Span Tables."

though only a fraction of the mass timber can be exposed.[502] As mass timber manufacturing and expertise continues to grow (60 project completions in 2018 compared to 10 in 2008),[503] the NBCC must keep pace with research to ensure it does not limit the market potential (and subsequent carbon reduction potential) of exposed mass timber. Exposed mass timber walls limit the ability to run services, hang décor, and otherwise customize a home (e.g. painting), while exposed ceilings similarly introduce biophilic material without the same limitations. Increasing the allowable ceiling exposure is important because it bears more value for potential developers and buyers which in turn enables further reduced embodied carbon.

Proposed Change

The fire dynamics of a mass timber compartment are affected by a multitude of factors including ventilation and room geometry, which the Code has no control over. As such, it is understandable to include a degree of conservatism in the allowances that are permitted. With that in mind, it is also unlikely that the difference in acceptable risk between Canada and the US is large enough to warrant such a large difference in allowable exposed mass timber ceiling. More research is warranted to investigate the differences between the RISE study and Canadian literature, to see if the conclusions reached by the IBC are applicable to the NBCC.

Additionally, in both studies which form the basis of current NBCC encapsulation requirements, the authors note that "had sprinklers been installed in the tests, flashover would not have occurred with effective sprinkler operations."[504] Even without sprinklers, one test with a fully exposed ceiling self-extinguished. Similarly, the RISE study showed that in all of the tests, the fire decayed continuously – although one compartment experienced secondary flare up of flaming as a result of smouldering CLT behind gypsum in the same manner that caused the Su et al. ceiling to fail.[505] However, in all five tests (which had 100% exposed ceiling and varying degrees of wall/column exposure), the ceiling showed significantly less char depth than accounted for in the 2 h FRR in the NBCC (19-54 mm of real char depth vs the required additional 78mm).[506] Clearly, further research is needed to assess the impact of sprinklering and ongoing smouldering. Additional research should also be conducted into the differential charring rates of ceiling and wall components as presented by Mitchell et al., as ensuring that mass timber elements

502. Gosselin et al., "Main Motivations and Barriers for Using Wood in Multi-Story and Non-Residential Construction Projects."
503. Natural Resources Canada, Canadian Forest Service, and Green Construction through Wood (GCWood) Program, "The State of Mass Timber in Canada 2021."
504. Su et al., "Fire Safety Challenges of Tall Wood Buildings - CLT Compartment Fire Tests," 62.
505. Su et al., "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction."
506. Brandon et al., "Fire Safe Implementation of Visible Mass Timber in Tall Buildings – Compartment Fire Testing," 102.

are sized correctly for their application has significant cost and carbon impacts.[507]

As is the case throughout history, new methods bring about new risks that are often unfamiliar to practitioners. Given the awareness of potential dangers and an increasing aversion to risk, relying on mistakes to inform regulation is inexcusable. With this in mind, the evidence that the existing structural fire resistance frameworks provides an acceptable level of risk, is based on historical experience.[508] Put simply, we have an approximate understanding of the degree of risk created by the existing framework, but we do not know how this performs relative to other possible options – after all, we only rarely observe significant failures.[509] [510] The introduction of EMTC represents a significant opportunity to create a break from tradition. Still, testing must be rigorous and thorough because regulation ought not to rely on conservatism in order to approximate what we do not know. Regulation should be evolving constantly to respond to new research, such as the work presented in the RISE testing. Given this research, and the incorporation of it into the 2024 IBC, the following change for Sentence 3.1.6.4.(6) is proposed (figure 3.50):

6. The exposed surfaces of mass timber ceilings within a *suite* need not be protected in accordance with Sentence (1), provided their aggregate area does not exceed

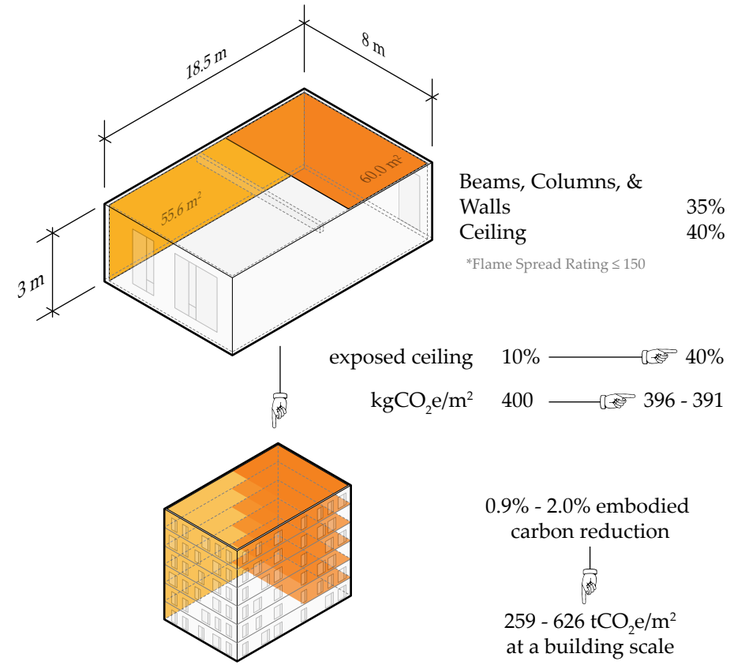
   a. 40% (increase from 10%) of the total ceiling area of the *suite*, where the exposed surfaces have a *flame-spread rating* not more than 75, or

   b. 100% (increase from 25%) of the total ceiling area of the *suite*, where

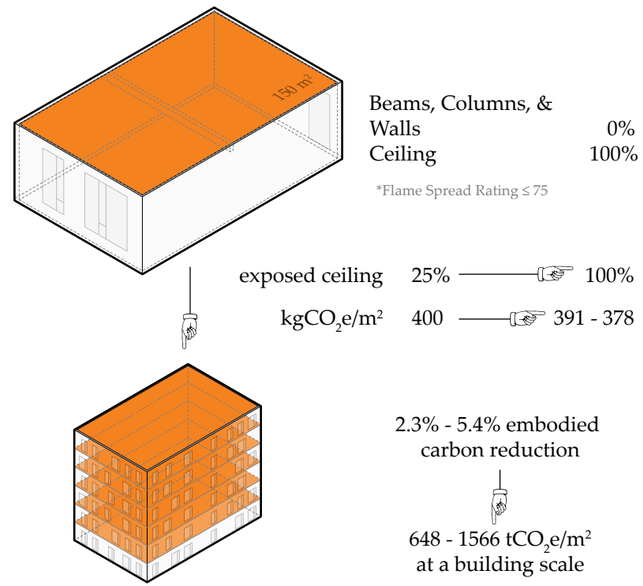
      i. the *suite* contains no mass timber walls with exposed surfaces, and

      ii. the exposed surfaces of the mass timber ceiling have a *flame-spread rating* not more than 75. (See Note A-3.1.6.4.(3) to (6).)

507. Mitchell et al., "Review of Fire Experiments in Mass Timber Compartments."
508. Bisby, "Structural Fire Safety When Responding to the Climate Emergency."
509. Law and Bisby, "The Rise and Rise of Fire Resistance."
510. Halliday, "Fire Disasters in Canada."



a) Compliant with proposed change 3.1.6.4.(6)(a)



b) Compliant with proposed change 3.1.6.4.(6)(b)

f 3.50

Proposed acceptable combinations of maximum exposed mass timber elements.

Barrier #7: Noncombustibility

Regulation and Interpretation

The foundation of the NBCC is built upon understanding material properties. The relative *combustibility* of materials has been of utmost importance since the inception of building regulation, tracing its roots over 2000 years back to ancient Rome.[511] Informed by experience and anecdote, there was an understanding that some materials are more prone to fire than others, prompting mandates to build with stone and brick rather than thatch and wood.[512] [513] Despite technological advancements, the integration of safety systems, and developed fire service, the inherent properties of the materials have not changed; wood burns very similarly today as it did a million years ago. However, the risks that *combustible* material presents when incorporated in homes is entirely different. This fundamental misunderstanding, that the risk presented by a materials' inherent properties cannot be overcome, has resulted in biases and overt conservatism that often means the NBCC requires construction in a higher carbon manner than necessary through mandating *noncombustible construction* (figure 3.51).

Testing standards provide for the quantification of the performance of materials with scientific data, though the results of testing rely enormously on the testing procedure and setup. How we come to "understand" material properties is equally important to what is revealed. *Combustibility*, the quality of being *combustible*, seems like an inherent trait however, the more it is investigated, the less concrete it seems. *Noncombustibility* (and inversely, *combustibility*) is determined in the NBCC by the testing standard CAN/ULC-S144 Standard Method of Test for Determination of Non-*Combustibility* in Building Materials, analogous to ASTM E136 which is used in the US. In this procedure, a 38 x 38 x 50 mm sample is dried at 60°C +/- 3°C between 24-48 hours, then cooled in a desiccator for 1 hour minimum before testing. The sample is weighed and two thermocouples (a type of thermometer) are attached to the testing apparatus: one is placed beside the sample and another above. The small vertical tube furnace, typically less than 300 mm tall, is heated to 750°C +/- 5.5°C and the sample is inserted, exposed on all six sides.

f 51

Excerpts from NBCC 2020.

511. Byles, "Fire and Its Consequences in the City of Rome in Antiquity, 390 BC - AD 410."

512. 32 George III, An Act to Guard Against Accidents by Fire in This Province.

513. National Board of Fire Underwriters, *Building Code Recommended by the National Board of Fire Underwriters.*

1.4.1.2. Defined Terms

Combustible means that a material fails tomeet the acceptance criteria of CAN/ULC-S114, "Standard Method of Test for Determination of Non-Combustibility in Building Materials."

Combustible construction means that type of construction that does not meet the requirements for *noncombustible construction* or *encapsulated mass timber construction*.

Noncombustible means that a material meets the acceptance criteria of CAN/ULC-S114, "Standard Method of Test for Determination of Non-Combustibility in Building Materials."

Noncombustible construction means that type of construction in which a degree of fire safety is attained by the use of *noncombustible* materials for structural members and other *building* assemblies.

3.1.5.1. Noncombustible Materials

(See Note A-3.1.4.1.(1).)

1) Except as permitted by Sentences (2) to (4) and Articles 3.1.5.2. to 3.1.5.24., 3.1.13.4. and 3.2.2.16., a *building* or part of a *building* required to be of *noncombustible construction* shall be constructed with *noncombustible* materials. (See also Subsection 3.1.13. for the requirements regarding the *flame-spread rating* of interior finishes.)

2) Notwithstanding the definition of *noncombustible* materials stated in Article 1.4.1.2. of Division A, a material is permitted to be used in *noncombustible construction* provided that, when tested in accordance with ULC-S135, "Standard Test Method for the Determination of Combustibility Parameters of Building Materials Using an Oxygen Consumption Calorimeter (Cone Calorimeter)," at a heat flux of 50 kW/m2,

a) its average total heat release is not more than 3 MJ/m2,

b) its average total smoke extinction area is not more than 1.0 m2, and

c) the test duration is extended beyond the time stipulated in the referenced standard until it is clear that there is no further release of heat or smoke.

3) If a material referred to in Sentence (2) consists of a number of discrete layers and testing reveals that the surface layer or layers protect the underlying layers such that complete combustion of the underlying layers does not occur, the test shall be repeated by removing the outer layers sequentially until all layers have been exposed during testing, or until complete combustion has occurred.

4) The acceptance criteria for a material tested in accordance with Sentence (3) shall be based on the cumulative emissions from all layers, which must not exceed the criteria stated in Clauses (2)(a) and (b).

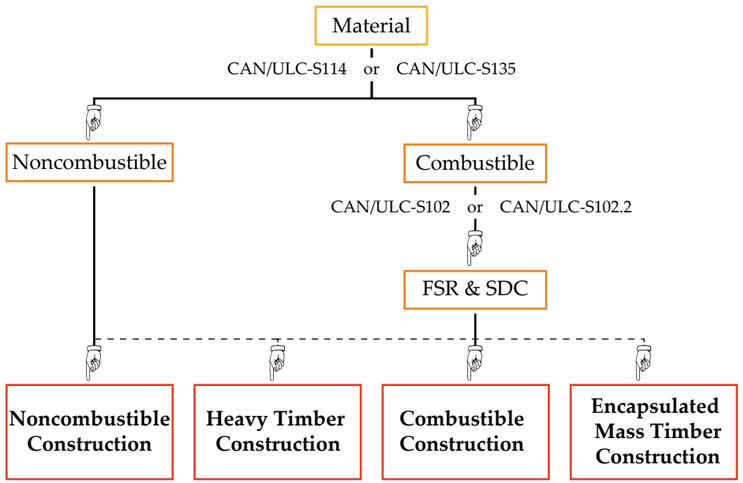
The test begins once the sample is inside the furnace and continues for 15 minutes. A material is deemed to be *noncombustible* (remember that the term "*noncombustible*" refers to the results of this test, not an inherent *noncombustibility*) if all specimens tested (typically three or more) meet the following criteria:[514]

1. An average temperature rise not larger than 36°C.
2. No flaming of the material past the first 30 s of the test.
3. A mass loss no larger than 20% of the original specimen or 22% provided there is no flaming and no increase in average temperature.

If the conditions are not met, the material is classed as *combustible* and the flame-spread rating (FSR) and smoke developed classification (SDC) of the material is tested in accordance to CAN/ULC-S102 (or CAN/ULC-S102-2 for foamed plastics), a variant of the Steiner tunnel test (figure 3.52). The purpose of incorporating this test was to determine the relative *combustibility* of different materials, with the expectation that more *combustible* materials would show more flame spread. The requirement to vary the test to accommodate for thermoplastic materials (which melt rather than transmit flame, resulting in low FSR despite high flammability) has been used to argue that this test is unsuitable for its task.[515]

The origin of the CAN/ULC-S114 testing apparatus, the vertical tube furnace, can be traced back to Robert E. Prince at the USDA Forest Products Laboratory in 1912.[516] The goal of his work was to explore the flammability of untreated timber with the purpose of investigating the effect of treatments and coatings – far from the determination of *combustibility* that it's used for today. Though the temperature increased from 200°C to 750°C, changed from gradual increase to fixed temperature, and the sample size decreased, the test setup and procedure has remained largely the same (figure 3.53).[517] The CAN/ULC-S114 test provides a binary evaluation of materials, determining whether they can ignite, otherwise contribute to temperature rise, and remain relatively stable. This approach reduces the complexity of materials in order to simplify decision-making processes for the building code.[518] The use of *noncombustibility* as a fire safety requirement was supposed to be a stepping stone from a prescriptive code that specified acceptable materials, to a performance one that listed acceptable, quantified limits. Instead, austerity measures cut funding for the development of this type of code, resulting in the continued, extensive application of this material characteristic 60 years later.[519]

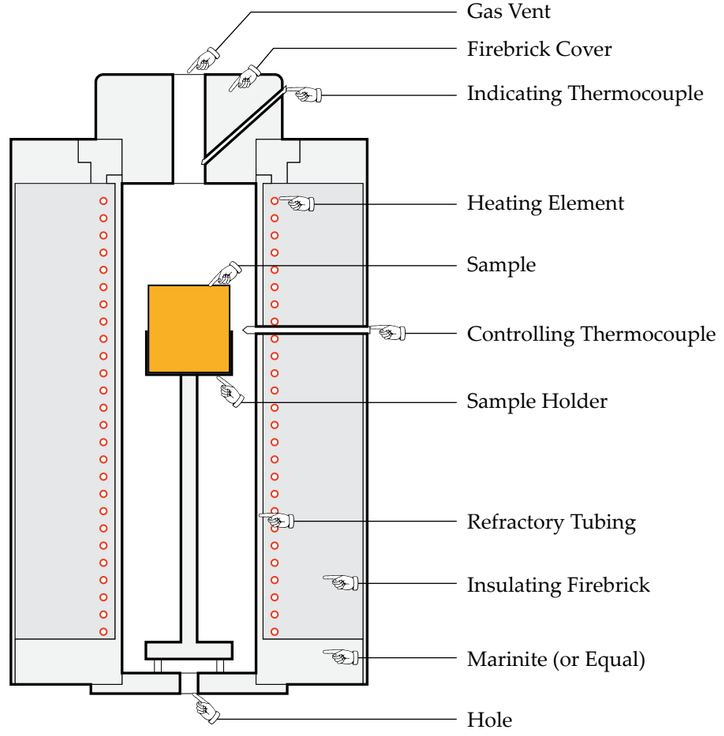
514. "CAN/ULCS114:2018, Standard Method of Test for Determination of Non-Combustibility in Building Materials."
515. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."
516. Robert E. Prince, "Preliminary Work in Fireproofing Wood."
517. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."
518. Hirschler, "Noncombustibility."
519. Keith Calder, Burning Up: Expert Interview #2.



f 3.52

NBCC 2020 material combustibility classification.

Combustible components are allowed in limited quantities in noncombustible construction. Heavy timber and encapsulated mass timber construction use combustible material in dimensions large enough to mitigate some degree of fire risk.



f 3.53

Vertical tube furnace diagram used in CAN/ULC-S114 to determine Noncombustibility.

The type of construction represents the most fundamental risk characterization and mitigation measure by the NBCC. As such, *noncombustible* materials are deemed suitable for use in any type of construction, whereas *combustible* materials are further classified by their FSR and SDC, with the NBCC significantly limiting their use relative to *noncombustible* materials. The addition of CAN/ULC-S135 Standard Test Method for the Determination of *Combustibility* Parameters of Building Materials Using an Oxygen Consumption Calorimeter (Cone Calorimerer) as an alternative to CAN/ULC-S114 for testing layered/composite materials in the 2005 NBCC addressed a significant shortcoming, however its application remains a binary test despite the potential for a range of values (like its ISO counterpart).[520] The determination of the 3 MJ/m^2 threshold of the CAN/ULC-S135 test is unclear and deemed unrealistic by some literature.[521] One possible answer is that the limit was derived from the total heat release from GWB,[522] which by the CAN/ULC-S114 standard would be deemed *combustible* (due to a loss of moisture and flaming paper facing) but can be classed as *noncombustible* through CAN/ULC-S135. If this is correct, it calls into question the validity of a test with its limits designed to confirm existing material biases.

Fire Safety Impact

The issue of using *noncombustibility* as a core tenet of the Code was described very clearly by R.S. Ferguson, the Head of the NRC Building Standards Section (1960's), in the aptly named technical note, The Problem of "*Noncombustible*" (1964): "[t]here was a time when everyone knew what was *noncombustible* and what wasn't. It was the difference between stone and wood. Manufactured products, however, have changed that. Gypsum wallboard is *noncombustible* but has a paper skin, cinder block incorporates up to 30 per cent *combustible* material, and sandwich panels of *noncombustible* materials are held together with *combustible* adhesives. Even steel is painted."[523] One might add to this anecdotal list that glass might not burn but its frames give way quickly, while heavy timber, once charred, does not readily flame. In essence, material properties, particularly in manufactured or composite products, are not as straightforward as they once seemed. In order to regulate these new materials, building code authorities had to define *noncombustibility*, with its first definition appearing in the 1960 NBCC (figure 3.54).[524]

The definition did, and still does, encompass materials with limited combustion, which highlights perhaps the most quintessential

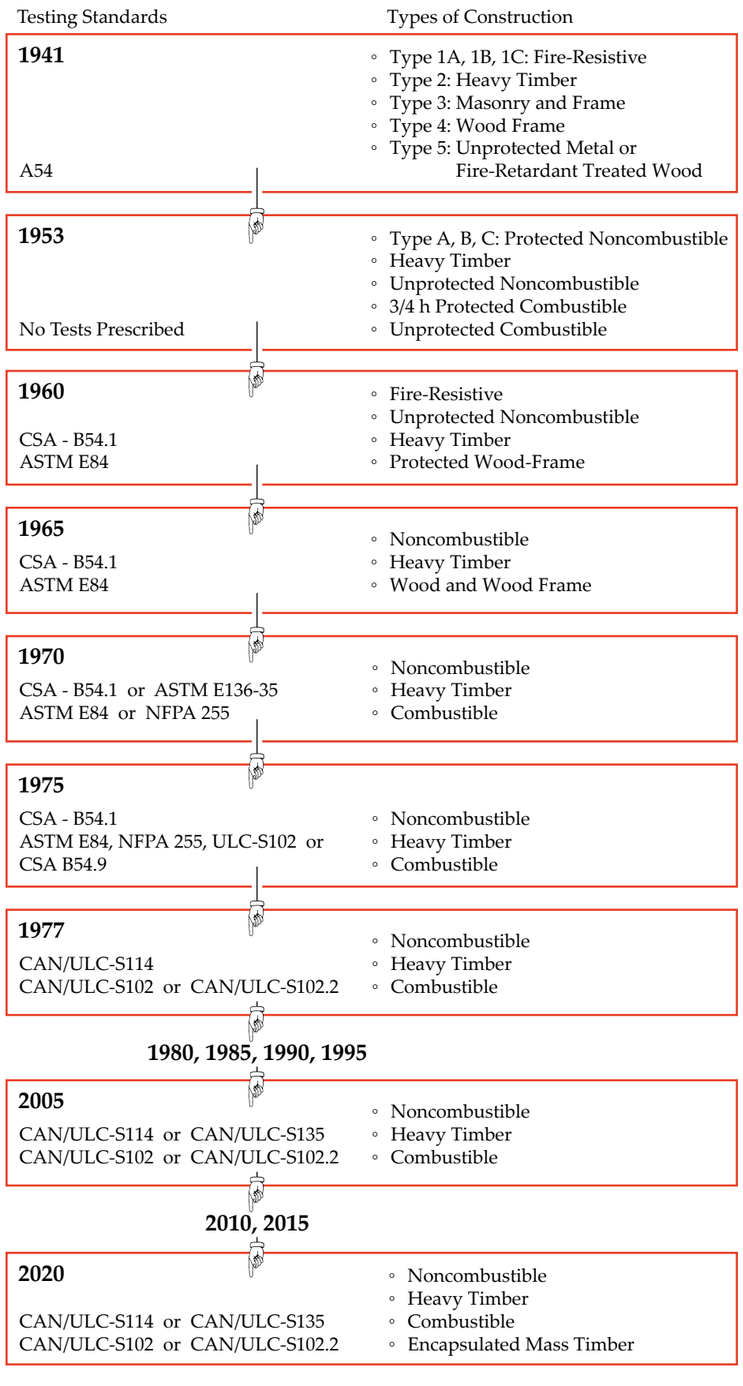
520. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."

521. Babrauskas, "Engineering Variables to Replace the Concept of 'Noncombustibility.'"

522. R. Onno and A.K. Kim, "Results of Cone Calorimeter Tests Conducted at the NFL/IRC."

523. Ferguson, "The Problem of 'Noncombustible.'"

524. Associate Committee on the National Building Code, "National Building Code of Canada: 1960" (National Research Council Canada, 1963). The definition, fairly interestingly, is not defined similarly to dark being the absence of light or cold being the absence of heat, instead combustibility is the absence of noncombustibility which assumes, rather counterintuitively, that noncombustibility is the default property.



f 3.54

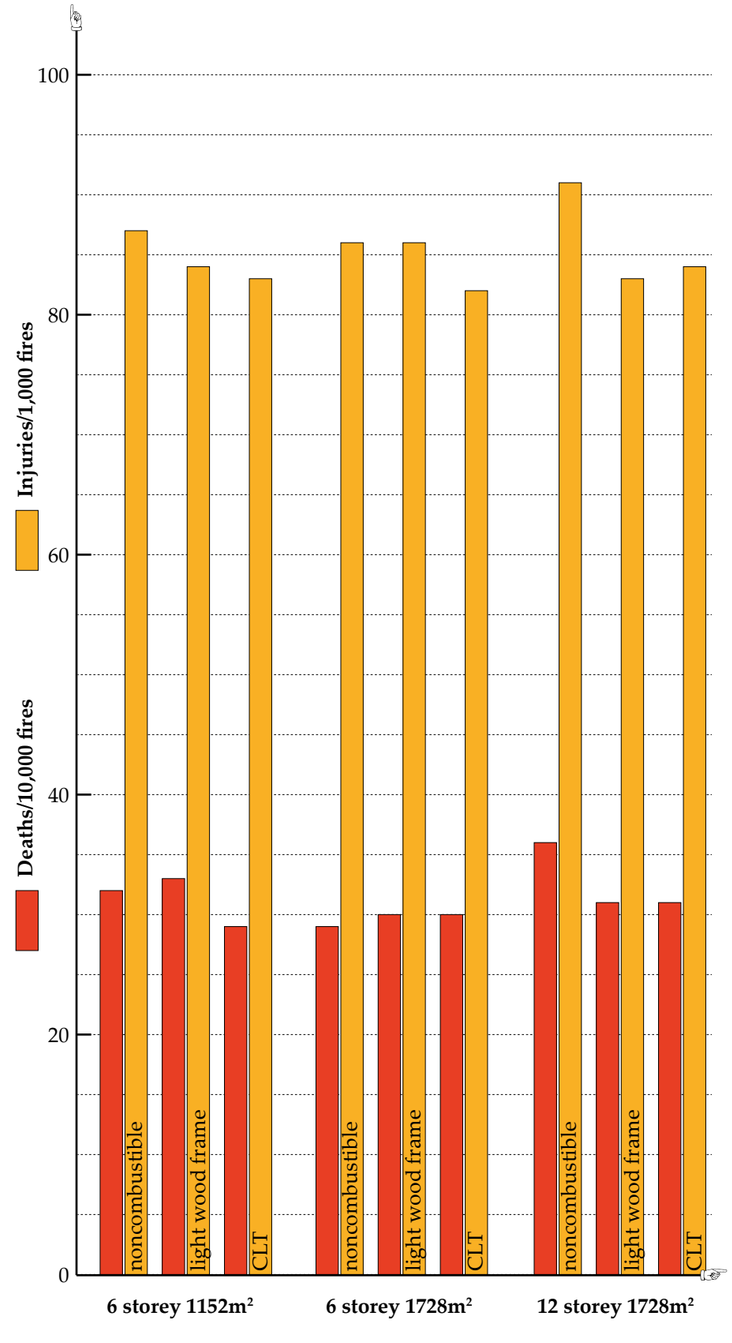
High level overview of the testing standards and construction types throughout the development of the NBCC.

issue of relying on *noncombustibility*; it draws a line in the sand and delineates materials into black and white categories, when the reality of the issue is a gradient. Ferguson goes on to identify five performance criteria that could be used to replace *noncombustibility*, tests for all of which had already, or have since been developed: fuel contributed, heat release rate (HRR); stability under fire, fire-resistance rating (FRR); heat transfer, FRR; flame spread, FSR; smoke and toxic fumes, SDC (although it does not measure toxicity). Despite this, *noncombustibility* remains the main, and in many cases, only, criteria for evaluating the fire safety of materials. Further, this note was written 20 years before fire alarms and sprinklers were thoroughly incorporated into the NBCC,[525] [526] which although they do not change material properties, enable significant protection from them.

Fire testing in general aims to measure a specific material characteristic related to fire risk and compare the results to other materials under the same conditions.[527] [528] Tests fall into three categories, relativistic, quantifiable, and full scale. The first, relativistic refers to tests that only provide a value relative to a baseline set by another material (e.g. FSR), whereas quantifiable tests provide a determinate value under specific testing criteria (e.g., cone calorimeter) which can only be compared to other data under the same conditions, and finally, full-scale tests aim to determine material behaviour under realistic conditions (and consequently are less comparable to one another). The testing standards for *noncombustibility* and FSR/SDC are only intended to rank the performance of one material relative to another and do not reflect real fire risk or potential contribution to a fire.[529] [530] Further, it is emphasized that the results will change if any of the following parameters are changed: size, shape, or location of the sample, exposure temperature, oxygen supply, and the location of the thermocouples.[531] Additional limitations which reduce the applicability of the *noncombustibility* test to real scenarios are the exposure from all sides, size of the sample, smoke generation/toxicity, and test temperature (which is higher than aluminum's melting point of 660°C).[532]

These limitations mean that the results are apt to change in every scenario other than the one they are testing. This test method provides no insight into the thermal response or chemical breakdown of the material. Further, the material is tested in isolation, which may be entirely different than its intended environment. For example, a piece of wood stud (approximately the size of a chicken egg) is tested in isolation, when in practice this material is usually surrounded

525. Max Lakkonen, "The History of Modern Water Mist Fire Protection."
526. Calder and Senez, "A Historical Perspective on Building Heights and Areas in the British Columbia Building Code."
527. Janssens, "Fundamental Measurement Techniques."
528. Elizabeth Weckman, Burning Up: Expert Interview #3.
529. Elizabeth Weckman.
530. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."
531. Nagy, "Determination Of Thermal Properties Of Mineral Wool Insulation Materials For Use In Full-Scale Fire Modelling."
532. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."



f 3.55
Risk of death and injury according to construction type and building size.

by other materials like insulation and GWB. Driven by the desire to better understand fire dynamics and fire safety, quantitative approaches to describing material behaviour under fire conditions have been developed - typically using calorimetric measurements. Examples of these which have acquired global recognition and adoption include the bomb calorimeter test, single-burning item test, room corner test, and cone calorimeter test.[533]

Beyond the (supposedly) simple material classification of *noncombustibility*, the impact of this characteristic on fire severity outcomes is increasingly being reconsidered. Fire safety in buildings is a multi-layered solution, which although the NBCC forms its basis with materials, the whole picture is significantly more complex. Zheng et al. performed a novel study using the National Fire Information Database (NFID) in Canada to research the impact of *combustibility* on building safety. The study uses Canadian data to evaluate the number of fatalities, injuries, fires requiring extinguishment by fire department, and the spread of the fire in residential buildings up to 6-storeys.[534] Though current regulations allow up to 6-storeys of both construction types, there are likely limited examples of 5- and 6-storey *combustible* construction given their recent inclusion. Despite this, NBCC regulations operate under the assumption that these taller buildings have the same risk as lower ones. Similarly, the study does not measure fire impact on the building beyond fire spread, however the extent of damage to the building is governed by the FRR which aims to provide a time period in which the building structure will remain unharmed. The study found that, although the raw data showed that *combustible* buildings had poorer fire results, once protective systems were accounted for, the type of construction did not have a significant impact on any of the severity outcomes.[535] The research highlights the role of sprinklers and smoke alarms for their importance in alerting occupants and suppressing fire growth. These findings are supported by a modelling study which found that the difference in occupant fire outcomes in mid- and high-rise residential buildings is negligible between *noncombustible*, *combustible*, and mass timber *construction types* (in fact it found that both light-wood frame and CLT construction were safer than *noncombustible construction*) (figure 3.55).[536]

Embodied Carbon Impact

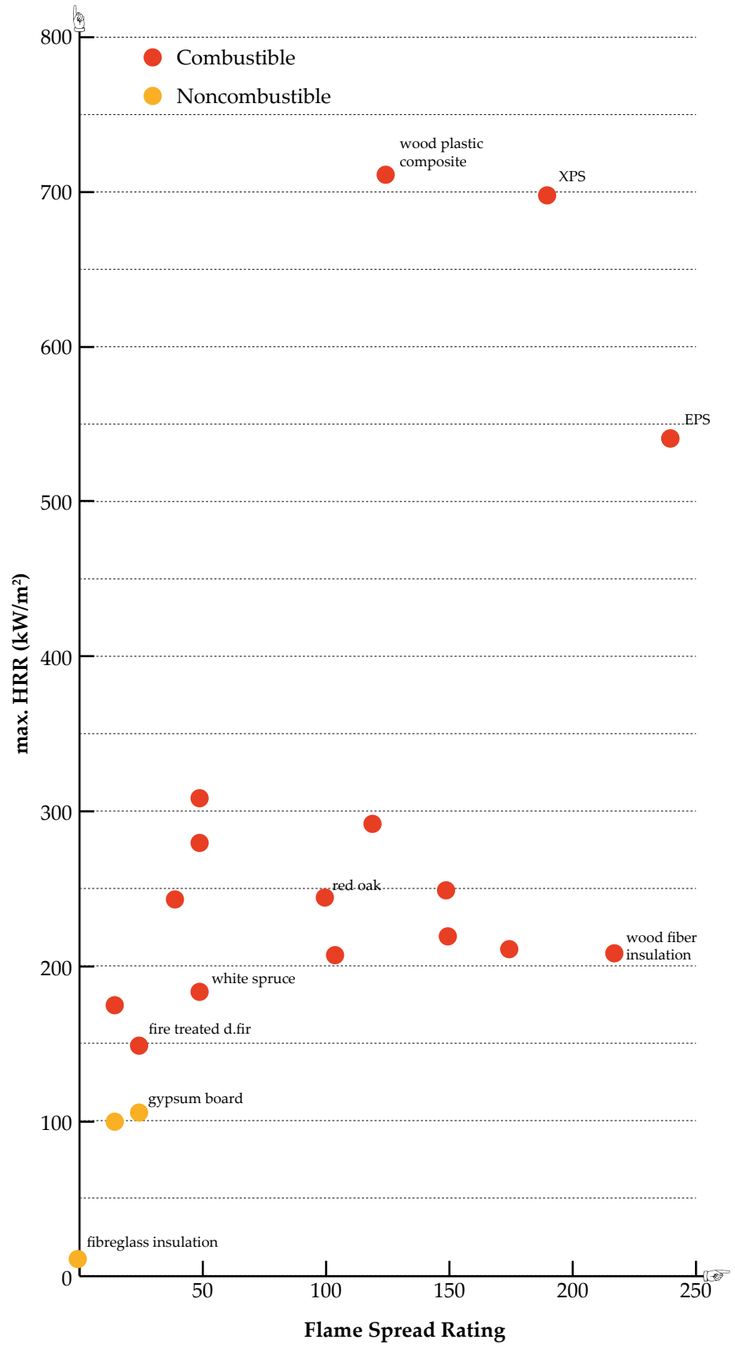
The use of *combustible* material is restricted throughout the NBCC with the purpose of limiting fire risk, to the detriment of embodied

533. Sadaoui et al.

534. Zheng, Garis, and Pike, "Fire Severity Outcome Comparison of Apartment Buildings Constructed from Combustible and Non-Combustible Construction Materials."

535. Zheng, Garis, and Pike.

536. Zhang, Mehaffey, and Hadjisophocleous, "Case Studies of Risk öto öLife Due to Fire in Mid ö and High öRise, Combustible and Non öcombustible Buildings Using CUrisk."



f 3.56
Comparison between flame spread rating and peak heat release rate of common materials, coded by combustibility.

carbon. Unfortunately, materials that are low carbon also tend to be *combustible*; both properties are a result of their biogenic nature. Natural materials tend to require lower energy to extract and process than manufactured ones and have the added benefit of being renewable. They also often store carbon through the absorption of CO_2 during their growth. While this thesis takes the 0/0 approach, where all stored carbon is eventually released into the atmosphere or carbon cycle again, sequestering carbon has the benefit of holding carbon in the present with the potential for reuse or low carbon end-of-life processes when the time comes.

This is not to say that all low-carbon materials are *combustible*, nor that all *combustible* materials are low carbon. There are a number of important materials which are both low-carbon and *noncombustible*, including fiberglass batt and mineral wool insulations.[537] Similarly, there are a number of products which use recycled *noncombustible* material to achieve a low embodied carbon product without large fire risk.[538] However, there are an abundance of materials which fall into the *combustible* and low embodied carbon overlap including: bamboo, wool, straw bale, cellulose, wood fiber, cork, linoleum, thatch, and timber.[539] Replacing *noncombustibility* with a performance metric may allow for greater design flexibility in addition to providing a clear target for innovative materials to meet.

The removal of *noncombustibility* as a determinant for use may be impactful for embodied carbon, however it does not mean that all *combustible* material is now permissible, it still must meet other performance targets. Cladding and insulation hold large carbon reduction potentials,[540] and moving towards HRR (or other testing standard) would remove or equalize some of the current inequities presented by the *noncombustibility* categorization binary (figure 3.57). The potential effects of altering these requirements can be seen through numerous examples of low carbon buildings in other countries.[541] For example, the Knudrisraekkerne and Lisbjerg Bakke projects in Denmark provide low embodied carbon housing, but rely on *combustible* elements outside of the bounds of the NBCC to do so (figure 3.58 and 3.59). Further, boundary pushing projects like the Cederhusen in Sweden suggest that substantial reconsideration of the NBCC's approach to *combustibility* is needed.[542]

The role of *combustibility* limits both building height and size, structural materials, and the materials of all constituent parts. The embodied carbon implications of these requirements are analyzed in Barrier #4, Barrier #5, and Barrier #6 (although material

537. Geoffrey Turnbull et al., "Embodied Carbon Values in Common Insulation Materials."

538. "Low Carbon Building Materials - K-BRIQö."

539. CINARK, The Royal Danish Academy, "The Construction Material Pyramid."

540. Magwood, Bowden, and Trottier, "Emissions of Materials Benchmark Assessment for Residential Construction."

541. Andersen et al., "Whole Life Carbon Impact Of."

542. Folkhem, "Cederhusen."

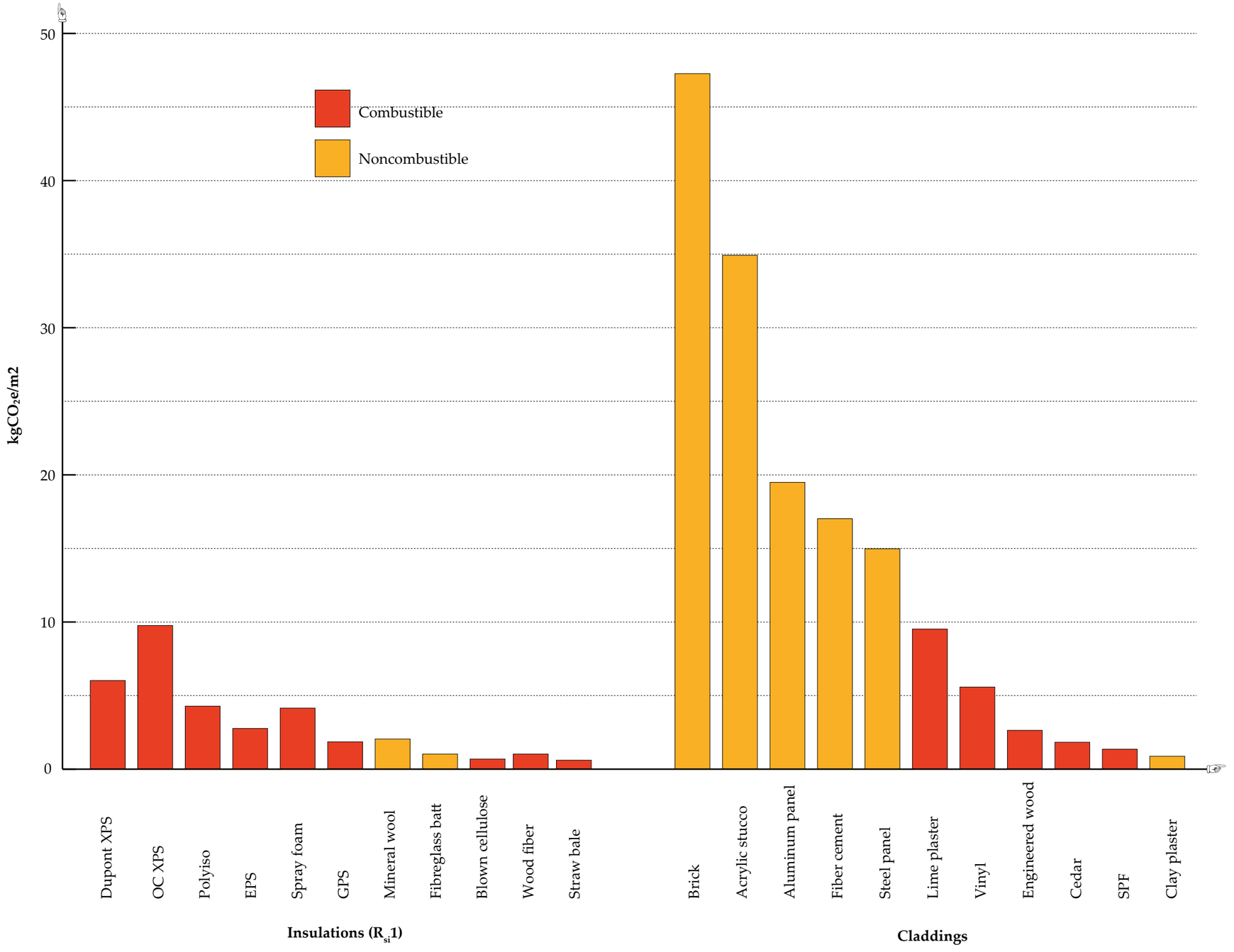
implications are wide ranging and touched upon in Barrier #2 as well). Expanding *combustible* construction height limits in a similar manner to *noncombustible* construction could result in up to 8% less embodied carbon per capita. There are significant embodied carbon savings to be found in the substitution a of *noncombustible* structure for a *combustible* one; up to 70% of the embodied carbon in a building's structure can be avoided by switching to timber.[543] A further 5.4% from reducing encapsulation requirements could push projects to approximately 37% of their original per capita *noncombustible* emissions (assuming the structure accounts for 1/3 of total carbon), to say nothing of the potential for further adoption and density. While it is unlikely that all of these reductions stack on top of one another, by providing multiple pathways to lower carbon design they increase the likelihood of doing so (figure 3.60).

Proposed Change

Understanding material properties is of critical importance today and as we move forward into the future. The ability to transmit both fire and carbon are existential threats, though they act at different scales. Reconsidering *noncombustibility* as a primary principle of fire safety is essential in order to address tightened levels of acceptable risk and embodied carbon. The current application of this concept is reductive in a time where specificity and a deeper understanding is both possible and necessary to remove barriers to low embodied carbon construction.

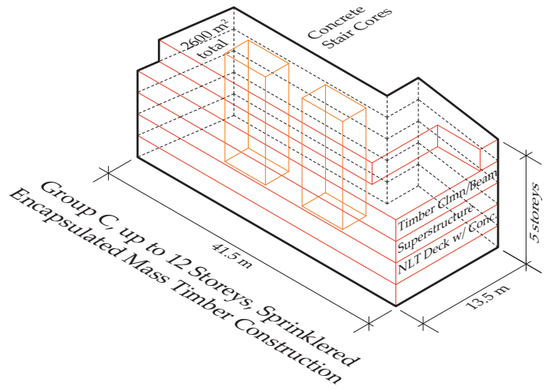
Proposing an alternative measure for *noncombustibility* is outside the bounds of this thesis; it is part of the much larger project of redefining, and defining for the first time, the performance metrics of acceptable fire risk. The reconsideration of this concept is required to transition from the current objective-based code to a performance-based one. The identification of acceptable substitutes requires significant investigation and further testing in concert with holistic approaches to fire safety. This is not to say that *noncombustibility* has no place in the NBCC, nor that contemporary fire testing methods within the NBCC are ill-suited to their task; indeed, the solution likely already exists within our Code but needs to reframed. The re-evaluation of *noncombustibility* should not happen in a vacuum of fire safety. The testing standard's broad implications on embodied carbon in the Code show its potential unintended consequences which need to be considered in future categorizations. As we continue to understand

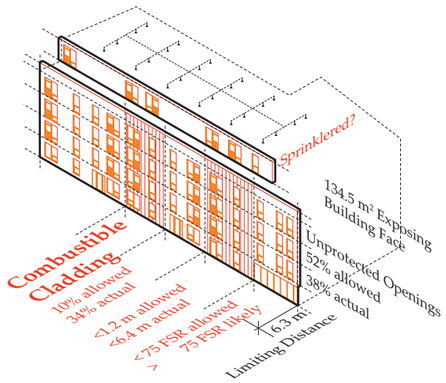
543. Himes and Busby, "Wood Buildings as a Climate Solution."

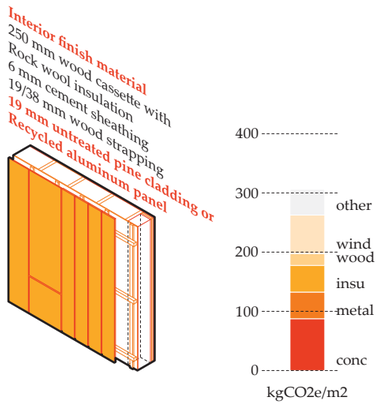


f 3.57

Embodied carbon of common insulations and cladding materials.



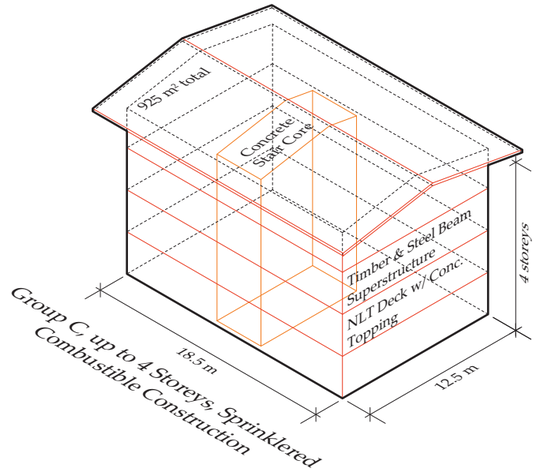


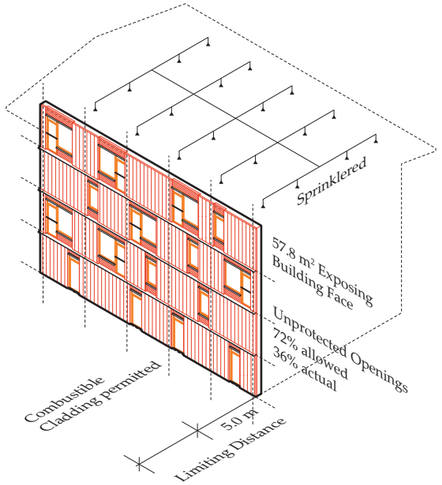


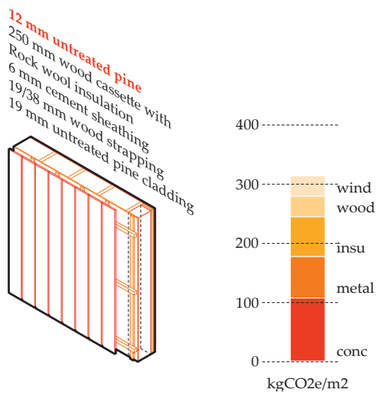
f 3.58

Analysis of Knudrisraekkern (Denmark) through the NBCC.

This building exceeds the allowable limit for combustible cladding. It is uncertain if it is sprinklered, which is a requirement for Group C, up to 12 Storeys, Sprinklered category.







f 3.59

Analysis of Lisbjerg Bakke (Denmark) through the NBCC.

Although this building is largely compliant, which gives hope to low carbon design in Canada, its internal finish may exceed the FSR limit in the NBCC. Further, its form and density, though permitted, is rarely built in Canada as a result of lot size, financialization, and zoning bylaws.

and codify material properties and testing methods better, we can begin to address the way that they inform construction assemblies, how those assemblies shape buildings, and how the buildings create neighbourhoods and cities.

The CAN/ULC-S114 Standard Method of Test for Determination of Non-*Combustibility* in Building Materials has comparable tests in the US, New Zealand, Japan, and the EU. Canada assesses *combustibility* through a binary system instead of a ranked or tiered system used internationally. The approach simplifies decision-making in a reductive manner. This approach may provide clarity for policymakers creating the building code and practitioners interpreting it, but it reduces the ability of qualified professionals to determine the applicability and systems approach to fire safety. The test also has other benefits, its reduced size decreases cost, increases control, and allows for repeatability of results. It does not however, provide any information regarding a material's contribution to a real fire, appropriately assess materials that are heterogenous or layered, mimic real fire exposure, enable the evaluation of full-scale uses, or collect data on smoke quantity and toxicity.[544] CAN/ULC-S114 also has limitations in its assessment of materials with low melting points like aluminum, which is classified as *noncombustible*, but will melt before reaching 750°C, high chemically bound water content like GWB, and self-heating insulations like mineral wool.[545] [546]

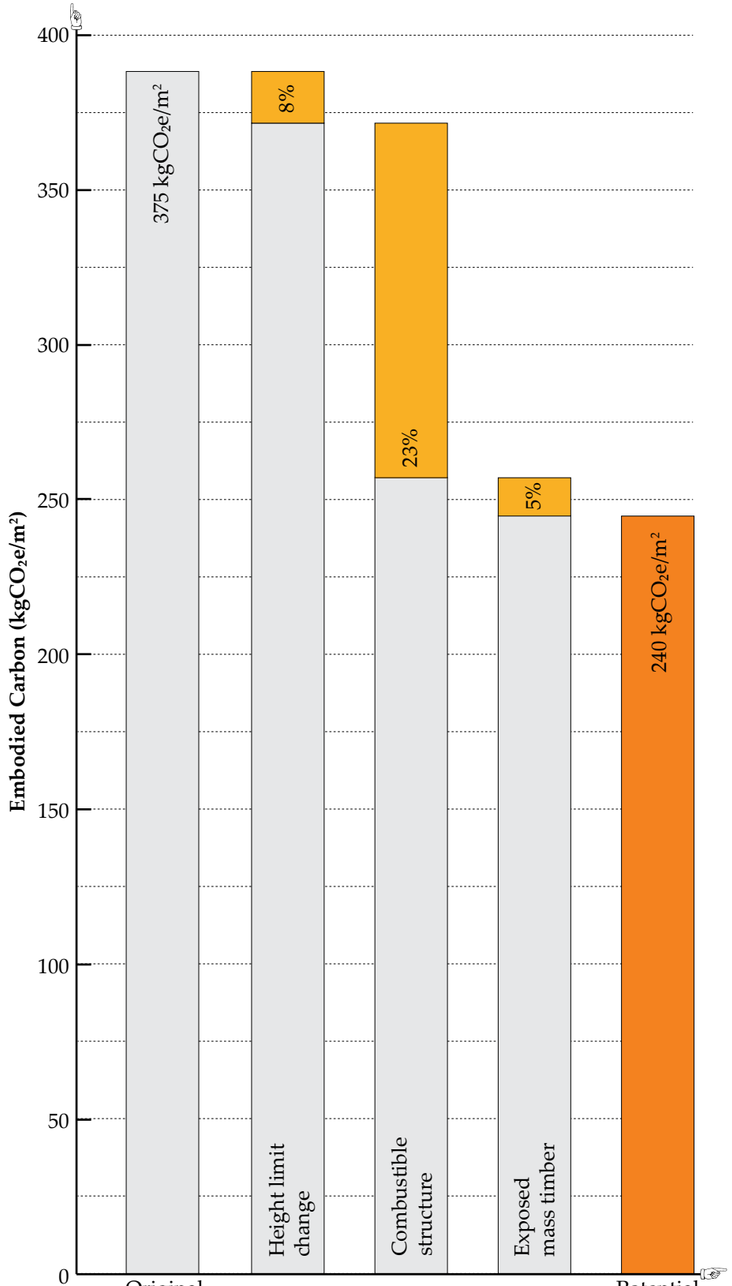
Babrauskas, very convincingly, lays out the case for replacing *noncombustibility*. Historically, *noncombustibility* was envisioned to address four fire safety concerns: fire spread in void spaces, excessive contribution to the fuel load, ignition of materials near heat sources, and flame spread on interior surfaces. The first has already been addressed through firestopping. The second is the result of a misunderstanding of fuel loads in buildings; occupant fuel loads far exceed the contribution of building component during the required FRR (the period in which occupants are exiting the building and firefighters are conducting their operations). Further, once a room reaches flashover, it becomes ventilation-controlled meaning that any additional fuel load generally does not increase fire size, it simply prolongs the fire. The third concern is absolutely valid, and *noncombustibility* should remain a requirement as it addresses ignitability and not flame spread. The fourth, the spread of fire across interior spaces, particularly in occupied spaces and egress routes, should be addressed through both HRR and FSR. The author proposes that two separate tests or a single large-scale HRR test is needed to capture both variables.[547]

544. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."

545. Nagy, "Determination Of Thermal Properties Of Mineral Wool Insulation Materials For Use In Full-Scale Fire Modelling."

546. Sadaoui et al., "The Evolution of Reaction to Fire Classification of Materials."

547. Babrauskas, "Engineering Variables to Replace the Concept of 'Noncombustibility.'"



f 3.60

Waterfall graph of reductions identified by this thesis that are concerned with noncombustibility.

Conclusion

Summarized Findings

While the importance of embodied carbon to reduce the whole life GHG emissions of buildings is only recently becoming widespread knowledge, the regulatory confines of the NBCC to these reductions remains, until now, unresearched. Given that embodied carbon regulations are currently in place in various AHJs within Canada and that they will be included in the 2030 NBCC, understanding the role of fire safety with respect to low embodied carbon housing is imperative to reconciling these often-competing objectives. It is essential to identify, quantify and propose solutions to the barriers that fire safety poses to low carbon construction so that architects are able to design with reduced embodied carbon in the context of the existential consequences of climate change.

This thesis highlights the potential of missing middle and mid-rise housing to provide low embodied carbon homes along with an exploration of the embodied carbon regulatory framework. Taken together, they underscore the critical need to enable lower carbon design than is possible under current NBCC provisions in order to address the climate and housing crises. These frameworks trace directly back to their origins in the early days of London nearly a millennium ago and continue on the tradition of prohibitively regulating noncombustible building material which began at least 2000 years ago in Rome. Though the NBCC is a relatively new document, its history is fraught with arbitrary and often scientifically baseless changes which reflect the process of advancement through responses to significant fire events. These regulations place extensive control on the construction of combustible buildings, inadvertently restricting Canada's ability to build with wood, its primary low embodied carbon material. As capabilities to deal with fire risk have increased, the Code has made some allowances which permit construction of low embodied carbon housing, most notably the increase from 4 to 6 storeys of combustible construction and the adoption of encapsulated mass timber as a new construction type. Despite these advancements, the NBCC relies upon a framework developed as an interim solution on the way to performance-based regulations in the 1960's, many of which require a larger degree of embodied carbon than is necessary to maintain the existing level of fire safety.

These barriers exist at a number of scales that exemplify the Code's approach of prescribing the fire safety of individual components rather than considering the holistic risk, and risk mitigation factors, of a building. At an urban level, the minimum width of access routes contributes to the creation of excessively wide roadways to deal with poorly defined access and at-scene space requirements for large North American fire trucks. The regulation adds embodied carbon by necessitating significant pavement use and encourages lower density development. Similarly, the intertwined origins of zoning documents and building codes, which proposed land use restrictions under the guise of fire safety, has resulted in contemporary zoning documents that limit mixed and multi-unit residential land use which restrict low embodied carbon development in an urban context.

Within these urban contexts, the formal development of buildings also has embodied carbon limits. Two-stair egress requirements, largely the product of cost-based decision making in NYC in the 1900s, result in sub-optimal floor plate efficiencies when compared to single exit stair buildings. Less efficient building plans increase the amount of area and embodied carbon required to house the same number of people without any clear additional benefit. Additionally, the definition of building height encourages below-grade construction; basements are significantly more carbon intensive than above-grade floor area, yet they are not restricted in the same manner of fire safety. Altering the definition will allow the same building volume to be built above grade at a lower embodied carbon cost. Expanding on this, the actual limits of building area and building height of combustible construction also have embodied carbon implications, given the reductions possible by switching to a timber-based structural system.

Moreover, on the material scale, requirements for the encapsulation of mass timber elements in the new EMTC may be more onerous than necessary. Encapsulation requires gypsum board to cover the mass timber elements, adding embodied carbon and obscuring the wood from view which may limit the adoption of this construction type. Finally, the validity of noncombustibility is called into question, which has wide ranging effects given its multitude of uses throughout the Code.

Further Research

The barriers identified by this thesis only form a fraction of the research required to develop a holistic understanding of the impact of Part 3 regulations (let alone the whole NBCC) on embodied carbon. There are many other potential barriers to low embodied carbon construction which were identified through the combination of interviews and literature reviews.[548] [549] Unprotected openings in combination with limiting distance have important embodied carbon impacts through the prescription of noncombustible wall construction and cladding type. Similarly, the requirements for including combustible cladding and combustible insulation limit their widespread inclusion and pose significant carbon reduction potential through their large area of building envelope.[550] [551] [552] [553] Other requirements, especially as they relate to the integration of fire safety into existing buildings and mechanical systems (e.g. sprinklers and smoke dampers) warrant further research.[554] The breadth of barriers identified (and the ones listed above) indicate the meticulous manner with which the building code must be considered for its impacts on embodied carbon in the future.[555]

The proposed changes to the Code should be taken as a starting point (or in some cases, counter-points to other proposed regulations) for future regulations rather than as an all-encompassing solution. They are intended to provide a considered approach to provoke revision and, although the proposed solutions attempt to moderate a number of facets, they certainly emphasize embodied carbon reduction over other considerations (e.g., financial). The work presented in this thesis will be put into practice through reformatting the information into code change requests to be submitted to the Canadian Board for Harmonized Construction Codes (CBHCC) in order to catalyze real change. More research may be needed to quantify the impacts of each barrier with greater clarity and propose solutions with greater detail. However, it is important to note that many of the existing regulations within the NBCC were implemented without comprehensive study. While the barriers were identified in an acupunctural approach (in line with the traditional method of Code development), as a whole, they suggest that a new framework for evaluating Code stipulations may be needed in order to approach regulations from a holistic, multi-faceted understanding.

548. Van Coile and Maeso, “Methodology for Evaluating the Safety Level of Current Accepted Design Solutions for Limiting Fire Spread Between Buildings.”

549. McGuire, “Fire and the Spatial Separation of Buildings.”

550. Nguyen et al., “Assessing the Combustibility of Claddings.”

551. Chen et al., “Fire Risk Assessment of Combustible Exterior Cladding Using a Collective Numerical Database.”

552. Mehaffey, “Fire Performance of Combustible Insulation in Buildings.”

553. Knudson and Thomas, “Wood Fibre Insulation Demonstration Buildings.”

554. Gritzo et al., “Environmental Impact of Automatic Fire Sprinklers.”

555. Roberts, Webber, and Ezekoye, “Why and How the Sustainable Building Community Should Embrace Fire Safety.”

Significance

This thesis meets its primary goal of identifying the regulatory barriers to low embodied carbon housing within Part 3 of the NBCC. The work analyzes and illustrates the development of the NBCC for the first time – clearly laying out the primary consideration of each time period. Further it synthesizes research from two desperate pools of knowledge (fire safety and embodied carbon) and provides a new interpretation of the data in light of one another. Pursuant to this, the research quantifies the impact of each barrier on fire safety and embodied carbon which leads to the proposal of a set of solutions to each barrier. Though the identification of barriers and implementation of solutions will not inherently reduce the embodied carbon of housing in Canada, it provides an avenue for this work to take place. Taken together, the barriers presented by this thesis present a view into the previously unexplored intersection of fire safety and embodied carbon reduction in the NBCC and argues for embodied carbon to be integrated as a core consideration of all regulations in the Code. As a whole, this work begins to unravel the inherently intertwined nature of fire safety regulations and embodied carbon - an essential task as Canada moves towards meeting the housing and climate crises.

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Appendix A

Interview with Keith Calder

MP:

Can you give me a short biography about yourself?

KC:

Sure. I did my undergrad at UBC in chemical engineering and followed it up directly by doing a Masters of engineering in fire, also at UBC. I finished in 2000 and started working right away for a building code consulting firm. I did that for a couple of years and then went and did forensic work in fire investigation for another couple years, then started my own company with a couple other people focussing on forensics initially and then getting into design.

We sold that company in 2015, so I worked for someone else for a couple years and now I'm back to my own thing with similar people I worked with before. We primarily do building design related [code consulting], but also accessibility, forensics, and fire modeling.

MP:

And the work that you do now that mostly has to do with alternative code solutions?

KC:

So the design work we do definitely directly relates to application and interpretation of the building code, specifically Part 3 and some of Part 9, but in forensics we also deal with interpretation of the building code in order to determine whether or not some aspect of a fire event related to a non compliance.

MP:

So, you've been researching for about 20 years, coming on 25?

KC:

Yeah, about 25 years. I started researching code before I started working. As a student project when I was at UBC, I developed a computer model to deal with part of the building code. Back then I was researching a topic called spatial separation, which is in Part 3

[of the building code], and in my current research, spatial separation is one of my main case studies in re-examining the building code.

MP:

How does your research engage with regulation in the construction industry? Do you have, or have you had a more direct role in that regulation?

KC:

I've been involved with providing reports for the provincial government, federal government, and municipal governments, mostly to do with interpretation and application of the code. I've been on national code committees, starting back in 2009; the meeting I have starting at 10 is one of my code committee meetings for the Fire Protection Standing Committee for Part 3 of the National Building Code. I've been on a building code appeal board as a member for British Columbia (BC). I worked for the province of BC for about seven months between different employments, so I've had quite a diverse involvement in building regulations to do with fire.

MP:

I think that leads well into question four about how the code has been developed, but before we go to the history, since you're on the Standing Committee now, can you talk a little bit about the direction you think the code is headed?

KC:

There are a lot of initiatives going on to try and make the code more responsive to changes and especially environmental changes. But there's a lot of tradition wrapped up in the code that is holding it back, and that's a bit of a roadblock too. There's an intent [for the code] to become more responsive, but I don't really see a plan at this point in time to getting around that traditional base to the code. I think there's a lot of goodwill, but not a lot of reasonable solutions to get there.

MP:

Like there's an intention to be responsive, but the base of the code is set out in such a way that it only allows for so much responsiveness?

What are some of those hard barriers that you're coming up against?

KC:

In the past, the National Research Council (NRC) was very much involved in the cutting edge of what was going on - when I discuss this it's mostly to do with fire - and I think they've lost that, especially in the last 10 years. I think there's less of a direct involvement in what's going on and less research that helps out practitioners. And because of that, I think there's less vision as to where we need to take things to solve the problems of today. There's an attempt to reach out by NRC to private organizations to team in order to help them try and overcome some of those barriers, which I think is very positive, but I think it's going to take a lot of time.

I believe there's a lot of bureaucracy around how the federal organizations and research organizations work. And so, while the intentions are there, I think one of the barriers is the [time that] bureaucracy takes and trying to get some of these changes to happen much more quickly.

There are things that are considered to be fundamental parts of the code, and those are the things that are really difficult to change and to address. These are things like egress, you know, one versus two stairs is considered to be a fundamental part of the code. Combustibility-noncombustibility is another thing considered to be a fundamental part of the code. And when I say fundamental, those are the things that are very much linked to tradition and something that has been called the tried-and-true methods. These are methods that really have been demonstrated through experience and time and because of that, there's a hesitation to pull back on those because of that long history of what I would say is perceived performance - not necessarily quantifiable performance.

MP:

Let's go to history for a second. How was [the code] developed? What were the key moments?

KC:

OK, so there was initially there was an attempt in Canada to develop a model code in the 1920s; the US was going through [the same] process in the 1920s. They couldn't identify a governmental agency in Canada that was willing to take on the role of overseeing that

model code development, so it was abandoned in Canada but kept moving forward in the US.

Canada revisited [model code development] in the 1930s, and of course, at that time, the US was already 15-20 years into it. The NRC was selected to lead the development of the building code, and they brought together a group of stakeholders that included government organizations, private organizations, trade organizations, and they had a couple of conferences. Their starting point was to look at what was done in the US; there's several quotes where they basically say, "we can do no better than what they have done." [The NRC] adopted a majority of what already existed in the US model code.

So, Canada's starting point was really adoption of what the US had and you can see that in the first National building code of Canada, which is the 1941 NBC. There are sections that are almost word for word the same as in some of the US model codes. It was published in 1942 and then World War Two happened, so things were shelved for a while and didn't come back until about 1948.

In 1948, they started reconsidering the 1941 building code and brought in a lot of, I would say, technical heavy-hitters, a couple people who were involved with the development of the '41 building code along with some new individuals. They decided that they wanted to take a more scientific approach to the development of the code, so they somewhat revamped the code structure and added in some scientific principles - and actually a couple of performance-based principles as well. You can see a couple of those in the 1953 NBC, but for the most part, they kept a lot of the tradition from the 1941 NBC.

There was a lot going on in the background, a lot of great ideas, and a lot of great initiatives from the publication of the 1953 National Building Code (which was published in 1954), right into the 60s. But in the early 60s, there was an economic downturn and austerity measures put in place; because of those austerity measures, a lot of initiatives that had momentum from the 1953 NBC were stopped. There wasn't a lot of funding; austerity measures kind of put stuff on hold. They just kind of carried on with what was already in the code.

A lot of the people who were involved in [the initiatives of the 40s and 50s] started to retire or leave the system. There's a kind of 30-year step with generational amnesia that [within] 30-year time periods usually you can find someone who was involved that you

can talk to and find out why a certain thing happened, but beyond those 30 years, it becomes much more difficult. So that transition started to happen at the late 60s, early 70s and you started to get to a point where people were forgetting how things had been developed originally, which then makes it more difficult for things to change.

So, you get things kind of continuing on from the 1950s. There wasn't a whole lot that changed until you hit the 1990s, where there was a real push to incorporate sprinkling as a solution - or more holistic solution. Originally, [sprinklering] was intended to included in all Part 3 buildings, but they had to pull back on that a little bit because of a lack of water supply in certain jurisdictions in Canada. Despite this, they still were able to get sprinklering in many more buildings by way of the building code. So that was a key point, but they didn't revisit some of the earlier solutions to see whether or not sprinklers addressed those hazards and those earlier solutions could be pulled back on. One example of this is combustibility.

The next big milestone was the development of the objective-based codes which happened in the early 90s around the same time that sprinklers are being further incorporated into the code and that went right through until the 2005 National Building Code where the objective-based approach was published. We haven't had a whole lot go on since then, other than what we're seeing now, with a lot of significant climate issues coming up that need to be addressed or at least incorporated into the building code. I think we're at that next point where we need a substantial change in the building code in order to be more responsive to those to those events.

MP:

And those climate events that you're talking about, are you referring to the energy code and the introduction of encapsulated mass timber construction?

KC:

Yeah, I would say it's more from a fire perspective. We need to be able to support the other necessary changes in the building code. Because of the changes, because of the energy code, because of the changes to building envelope, the fire requirements are somewhat of an impediment to those changes in in some respects. With mass timber, because it's one of those fundamental [risk] parts of the code, we need to revisit that fundamental aspect to make sure that, from a risk perspective, that the earlier concern about how combustible stuff burns has been addressed. We need, from a fire

regulatory perspective, we need to be more responsive to remove those barriers or readdress them earlier, things that were considered as risks earlier.

MP:

In North America, it seems to me that sprinklering is seen as a kind of cure all for fire safety, whereas New Zealand and some European countries don't have the same sprinkling requirements even in tall buildings. I don't know how familiar you are with those codes, but could you talk a little bit about how they deal with the same risk?

KC:

I'll jump back in history a little bit here to [answer] it from the perspective of why North America is more heavily sprinklered [than] the rest of the world. It comes down to a conference that happened in 1903 in Europe and you can find a conference paper by Ira Woolson. He attended this conference and there was kind of a sprinkler, non-sprinkler faction at this conference. North America, because they their industrial development happened in the 1800s or [at least] significant progress in industrial development, they found sprinklers as a solution to a lot of fires that were happening in industry. When [significant] fires started happening in residential buildings and non industrial buildings, the US found sprinklers as a quick and simple solution and applied it directly into their building codes as that key solution. Whereas in Europe, they went down a different path and didn't necessarily see sprinklers as a solution. They primarily had noncombustible construction and so there was a divergent focus on solutions to the fire problem.

And then, because Canada primarily adopted the US model codes, they adopted that whole sprinklering solution. North America has kind of continued on with [sprinklering] as being the key solution to the fire problem, whereas the rest of the world has been more balanced in how they've looked at a solution to [the same] problem. Without focusing on where international jurisdictions have gone, I think North America is focused a little too much on [sprinklering] as opposed to balancing out other solutions.

MP:

What is the role of combustibility in the NBCC and how this is this

different from flame spread rating and fire resistance rating?

KC:

Combustibility is considered both a hazard and a risk mitigation measure. Noncombustible material and [noncombustible] construction is used as a solution to limit fires. Combustible material is differentiated as a function of its nature into two categories in the building code: you have contents and you have building components. Combustible contents are considered to be stuff that's generally movable, transient, and not really controllable, so it was determined years back that the building code was not really a document that you could use to control combustible content.

Instead of controlling it, they came up with a way of characterizing occupancies as a function of how much combustible content they might have. It was used as a way of characterizing the hazard associated with those occupancies. Building components, on the other hand, were those are those are things that are generally not movable. They're part of the building structure and are viewed as being controllable by way of the building code, and they're generally controllable in terms of combustibility. [Components are separated] into material and structure; material being things like surface material or minor components. Interior finish material was looked at more from where it was located and whether it would contribute to fire growth and spread or not. Structure was looked at [in a] black and white manner. Smaller buildings, you are allowed combustible structure but in larger buildings the structure has to be noncombustible.

Now if we go back to the whole combustibility question and the different between flame spread rating, fire resistance rating - flame spread rating is more a measure of comparable performance with limited, quantifiable application. It addresses surfaces with the intent of limiting early fire growth and spread, and to some extent a way of quantifying the severity of a material, whereas fire resistance is more of a quantifiable measure of performance that's intended to deal with later fire development and containment. I think you have to look at those nuanced views of combustibility and relate the hazard to the stage of fire development, and control relative to that stage of fire development.

MP:

Do you see combustibility largely being used in terms of life safety or in the protection of property? I think in some way life safety is really only concerned with the first hour or half an hour of a fire starting which might be better addressed by the fire resistance rating, whereas in the early codes, there was lots of concern about the protection of property and thus combustibility. Where do you see combustibility in that spectrum [from life safety to property protection]?

KC:

Yeah, I'd say it relates more to property protection with the exception of things like interior finishes – so the things that [need to be] controlled relative to early fire growth and development. These things are more related to life safety than they are to property protection, but exactly as you mentioned: the bulk of the combustibility limits relate more to later fire development and full building involvement once people are out of a building.

MP:

Shifting gears a little bit, how does the type of building code impact the construction industry? How does manner in which we regulate impact the form and the type of buildings that we get?

KC:

There are there are very few actual, robust, complete, performance-based building codes out there. It's really difficult to say how, if we had the perfect performance building code, it would inform building development. But we do have some that are close internationally, and here we definitely have the objective base code and prior to that a more prescriptive base code. The prescriptive based code is generally, much more material specific or solution specific. It ends up guiding design quite significantly because your design has to fit in certain predefined boxes and those are very much linked to the past and traditional practice. When innovation comes along, it's very much a roadblock to innovation and keeps things stuck in the past.

The objective based code, because of its tight link to those old solutions, is not much better. I would say it's almost on par with a prescriptive code in its limitation on innovative solutions. So, it's a hold back to the innovative solutions, [compared to] if we were to have a full performance-based code that would allow the use of best

practice from certain groups. You can kind of already see [examples of] this with structural and building envelope [design]. There's a lot of innovation in building structure that you can see in the news, in designs, and to some extent [you can see that innovation in] building envelope and energy efficiency [in a way] that you don't see the same of in fire. You see it in those industries because those parts of the code are quite a bit more performance-based which allow a lot more best practice and leave design more up to professionals than up to the code requirements in building authorities.

And [switching to performance-based] was the intent when the code shifted to objective-based, they'd never intended for that to be permanent. It was considered to be a stepping stone to a full performance-based code, but a performance-based code that would sit parallel to a prescriptive code. You'd have a performance solution and you'd have a prescriptive solution sitting side by side. The bulk of buildings will be built under the prescriptive requirements and more complicated buildings would likely be done under the performance [code], but we do have some efficiency realizations that we can make relative to the prescriptive code. [If you think about it] like a "V", you have your performance at the top and your prescriptive at the top, but the piece that's missing is the connection at the bottom with the same basis information, the same assumptions. Once you know that basis information, you can use that basis information to optimize your prescriptive requirement and develop your performance requirement. That's the piece that's rarely talked about; I think it's the missing piece that allows us to move into the future and keep the codes malleable over time, both prescriptive and performance.

MP:

What's your experience been in challenging the code?

KC:

The comment that always comes up, especially to do with fundamental code items like egress and combustibility, is that you'll hear people say, "well, it's in the code. It's fundamental. It must be there for a really good reason. We don't know that reason, so you're crazy to change it." The thing that [overcomes] that is when you have the political will saying "this is going to change and we just need to find a way to change it." If you don't have that political force then dealing with those fundamental aspects of the code are incredibly

difficult unless you can come up with the [historical] basis behind it and highlight where things may have changed or where things may not be the same as when those requirements were developed.

MP:

I think that brings up a really important point about the political will behind these technical documents. It, in some way, completely explains the split between Part 3 and Part 9, a very fundamental split within the code. The delineation happened in the early 1900s because of classist sentiment and then was reinforced by the political need post World War II to quickly build a whole bunch of small houses to reward veterans.

I think that's a really interesting point to bring to light: it's not just right now that we have political forces behind code changes. Even the things that we now consider as the basis [of our code] were once political points.

KC:

And it's usually those external forces, so climate issues [and housing issues currently], that cause politicians to intervene in the building code. That's happened in the past as well. The UK, for example, had a very traditional, stagnant building code up until World War II. There was a significant amount of destruction in the UK and it required a lot of rebuilding which was the political will for them to revisit their building codes. There's actually a whole set of building code studies from the UK in the 1940s and 1950s because of the political will for change and because of that, the UK has a much more modern building code than what you see in Canada or the US.

I think [the single egress code change] is part of that whole shift. There was actually a shift before the single stair to do with combustible construction that came out of BC and that's the whole mid rise and then mass timber development. That was a political decision or primarily politically driven movement, that allowed those changes to occur. There is a general shift of momentum [happening now] that I hope continues to other parts of the code.

MP:

How is fire safety and fire safety equivalents assessed?

KC:

Yeah… yeah, well, so, right now it's all comparative.

The governing acceptable design is regulated by the primarily prescriptive requirements in the building code, and so we have to use those as our standard for what's acceptable and what's unacceptable. Because those are tradition-based, material-based, and also certain design-based, it very much limits what we can do as a comparison to that.

For the most part, when building authorities are reviewing alternative solutions and the proponent of an alternative solution has to do that comparison, the building officials are looking at the materials that the code is saying you have to use and saying "Well, what you're proposing is a different material, therefore, it's not as good as [the acceptable solution]" or "what you're proposing is a different design, therefore, it's not as good as [the acceptable solution]." In order to overcome that, there's typically a lot of things that are thrown in [by the proponent] that may have rational or maybe not. A lot of times that's sprinklering, or more sprinklering.

There are perceptions that need to be overcome and when we try to use fire engineering and fire science to address these problems, the building authorities we're dealing with aren't necessarily fire engineers or fire scientists and [they] don't necessarily understand the concepts. They know the code, and so to overcome that barrier [solutions that don't necessarily fit the problem] are what you end up with – something that my industry calls horse-trading.

MP:

What further research do you think is most pressing?

KC:

Statistical fire loss framework that aligns with the building code.

MP:

So that means determining what the causes of the fires and the factors that enabled the losses in the fire?

KC:

Exactly, but not so much what caused the fire, [instead,] what

caused the losses and how does that relate to our current building code requirements?

That'll help us determine, or provide more direct link between hazard and solution that [can be] kept more up to date, especially with the analysis methodologies we have today. [Using] Bayesian inference with that data, we can create models and then with new data update those models to better represent and determine the impact of those losses on the effectiveness of existing building code requirements and the development of new building code requirements.

MP:

And so that takes a kind of like a forensics approach where you're analyzing past fires.

KC:

That's right. UBC published a report where they looked at fire losses in larger combustible, non combustible buildings to determine the if the whether combustibility played a role in fire outcomes in sprinkler buildings - so that's a that's a really good example of the type of analysis [required].

MP:

So that means that means a lot better reporting on fire.

KC:

Yeah, and the reporting right now is very traditional. So [we need] a revamping of the whole reporting process and a detailed analysis of those stats. The other [thing we need is] the apex or the base of that V that we talked about before. We have to get there by looking at our existing requirements and analyzing those historically [in order] to pull out the basis information and determine whether or not those [base assumptions] are still viable. If they're not viable, we need to revisit and change that basis and so if they are viable then you can develop your performance requirements.

So that's the other piece I see missing: the historical analysis of our existing building code requirements and a reconsideration of the basis of those requirements.

Interview with Shoshanna Saxe

MP:

Can you give me a short bio about yourself?

SS:

Alright, so my name is Shoshanna Saxe, I am an associate professor in Civil and Mineral Engineering at the University of Toronto, the Canada Research Chair and Sustainable Infrastructure, and I direct the Center for the Sustainable Built Environment. I'm a civil engineer by training and started my career working in big infrastructure project design for subways and highways and big basements. Then I decided I was more interested in the problems [that] we didn't know the answers to than the ones we already knew how to do. So, I went back to school, got a PhD from Cambridge in engineering looking at life cycle thinking for a large infrastructure.

MP:

How long have you been working and researching in this field?

SS:

It really depends how you count, but I would say somewhere between 15 and 20 years.

MP:

It seems that there has been a shift in your recent research towards embodied carbon as opposed to operational [carbon], do you feel like there's been a shift in focus for your research? And if so, why?

SS:

Yes, there has been a shift, but that's not it. My early research focused mostly on large transportation infrastructure, I did a lot of work on subway systems and other aspects of transportation. Now I'm doing a lot more work on buildings, neighbourhoods, and cities. Transportation forms part of that [research], but the mass is dominated by the buildings. The reason for that shift is that I

answered, to my satisfaction, the questions I had about transportation infrastructure. We got to a point where we really know what the answers are technically. You can always sharpen your pencils a little bit more and dot more "i"s and cross more "t"s, but I think the field [now knows] what the life cycle impacts of different transportation systems are and how it trades off between construction operation, maintenance, and demolition.

So, I moved on to a new set of questions. Which is pretty typical for me, we spend about a decade on question and now I'm at the end of the next decade so I only have a couple more years in the kind of work I'm doing now.

MP:

Do you mind if I ask what direction you're looking at next?

SS:

I've already started doing work on transitions and time. It's one thing to say "we want things to change, we want a sustainable society, we want an equitable society, we want better infrastructure," but it means something very different, practically, if we say we want a sustainable society in five years or we say we want a sustainable society in 100 years because the suite of tools and the speed of change [alter] really dramatically. We are very bad at talking about time as a profession and as a society. I think it's something we need to start thinking about and talking about more because there are temporal horizons to the things we want to achieve [which impacts] our toolkit, what we should be doing, and how long we can wait. The longer we wait, the smaller our toolkit gets.

MP:

Could you talk a little bit about some of the factors that govern this shift? Or rather, the barriers to the shift to the sustainable city?

SS:

I'd say the biggest barrier is fear of change, which manifests all the way through our political and regulatory systems. There are little things like, until very recently in Toronto, even when it was legal to build a multi-unit building, it had to be smaller than what you could legally build for a single-family building. And that's silly, but it was on the books for ages, and it stopped all kinds of people

from building multi-unit buildings. It only just changed with the Multiplex law, but those types of little rules exist all over the place.

Then there's big [barriers] like single family zoning and minimum lot sizes all over the country, which incentivize low density construction, very expensive buildings, and very high consumption lifestyles. Then there are all kinds of things which aren't laws but are just destructive choices, like how much money Ontario is spending on highway infrastructure rather than things that would actually help with congestion, sustainability, and affordability.

There's also just full out politicking through the legal process. Again, Ontario being good example, the provincial government proposing banning bike lanes which is destructive to cost to taxation and to sustainability but signals a certain kind of politics to a certain kind of voter. Then we can go to the other side of the country where BC has made really big strides in legalizing affordable housing construction, which in many ways aligns with more sustainable housing construction because it's more multi unit, more single-stair access which create both more affordable buildings and more sustainable buildings.

That issue is coming up again in politics since it's very unclear, depending on who wins the next election in BC, if they will back off on those rules. All of this is tied up in culture, so it's very hard and scary for many people to talk about how much change needs to occur, and then [act] it. On the conservative end of the spectrum, people like will say that climate change isn't their issue, that it's not something they're aiming for, and on the progressive end of the spectrum, people talk about it a lot but are hesitant to follow through.

MP:

Can you talk about what the factors are that make a city low carbon or sustainable?

SS:

There are a couple big ones, one being how car dependent your city [is]. The more car dependent your city is, the less sustainable it will be and that is related to your land use. So how do you use your lands? Are you very spread out or are you low density but also have invested in other forms of transportation? Do you have

public transportation? Is the public transportation reliable and fast? Do you have good bike infrastructure so that people can bike safely? Is it well maintained?

Another big one is the emissions of upstream sources of energy. In Toronto during the late 2000s/early teens, Toronto benefited massively from the decarbonization of the Ontario electricity grid. Ontario got off coal and Toronto uses Ontario electricity. So, our electricity got way cleaner and actually in that time period we over-performed our climate targets. It looked for a long time that Toronto was doing really well, but it actually wasn't anything Toronto was doing. It was something Ontario did upstream of us that had a huge impact. If your upstream systems are sustainable, then your consumption will naturally be less impactful.

Those are really the big ones. I could continue for ages, but a lot of it is land use and upstream energy systems. There are other smaller ones like how well designed your buildings are. Are they well insulated so they don't overuse energy? Are they reasonably well designed so they're not overusing materials?

MP:

Referencing your recent paper about the missing middle embodied carbon intensities. Can you talk a little bit about the relationship between urban architectural forms and embodied carbon?

SS:

The really simple one is if you build single-family [homes], it'll be massively more embodied carbon than if you build any other form. From high-rise to mid-rise or even smaller 3-4 storey buildings, as soon as you move from building one unit per building to 3/4 units per building, you've made a huge impact in the sustainability credentials of our city, in terms of how many resources are needed to maintain the current population. That's a huge shift.

The other ones are things like setbacks and lot coverage. It's a version on the same [issue], right? The more land you don't use in one spot, the more you [have to use] somewhere else, and the more infrastructure you need to serve it. If you put 10 units in 10 buildings, you get 100 units. You need the linear infrastructure, the road, the sidewalk, the sewers, and the electricity lines to connect those 10 buildings. If you put 100 units in one building, now you

have much less road and much less water infrastructure per person.

The buildings themselves are the majority of the mass, so the infrastructure plays a role, but a smaller one. But the difference in resource use in, let's say, a water network between a reasonably dense community and one that's more spread out is 90%. It's 10 times worse in a more spread-out community. It's much, much, much higher and things like [bigger] setbacks mean that you're spreading out as opposed to using your resources intensively.

Coverage is related to setbacks, and lots of times we let people max. out their coverage without creating more units. We're often building more just to have a bigger home. The [issue] of height is a bit of misnomer; you can build very sustainable towers and you can build very sustainable low buildings. It's much more about design than height, but one of the things that height limits do is they force people underground or they incentivize [building] underground. [Regulations] say, for example, 2 1/2 stories of height across X amount of the city, [this] strongly incentivizes people to dig basements. And basements are the most polluting form of building construction. It's much better to have, from a climate perspective, the same floor area above ground than below ground. We don't have depth limits, but we do have high limits, which, again from an environmental perspective, is backwards.

People say, "well, what about sunlight?" The thing that yes, people need sunlight, but people also very badly need shade, and increasingly so in a cooling dominated world. Take one look at a streetscape anywhere in soon as it gets a little bit hot, and everyone is on the shady side of the street. There's a history of why people worry about sunlight: in old tenement style communities, housing was very dense and there'd be very little access to air or sunlight. That built in fear of extreme density and poverty together from the 19th and early 20th century which is still evident in our laws and our decision making about cities [today].

My favorite weird building code fact [is that] in the UK the rule about how far apart two houses have to be through their backyards, and it's the distance [at which] two men wearing white shirts can no longer see each other's nipples.[1]

1. 1. Phineas Harper, "Edwardian Morals, Thatcher and Bad Design – Why Britain's Homes Are so Hot," *The Guardian*, July 20, 2022, sec. Opinion, https://www.theguardian.com/commentisfree/2022/jul/20/britain-worst-built-homes-europe-extreme-weather-upgrade. The distance is 21 m for those who do not wish to read the whole article.

MP:

That is crazy.

When you were talking about single family housing being less carbon efficient, is that on a per bedroom basis rather than a square meter basis?

SS:

Yes, [on a per bedroom basis], but part of the reason is because single-family homes have a lot of space for very few people. In Ontario right now, new single-family homes on average are 30% bigger than ones built in the 90s and 100% bigger than ones built in the in the 50s. And there are fewer people living in them now than there used to be. It's a very inefficient use of space and materials, if you have a 5-bedroom home and only two people live in it - you have a lot of empty space and the bedrooms are absolutely massive. You need somewhere to keep your clothes, but you don't need, for instance, a couch and all the other things that we might put in a bedroom now.

I'm not saying people don't like having those things, but they certainly don't need having them. When we're talking about environmental limits or consequences, the difference between wants and needs is an importance differentiation.

So that's part of the reason why building single family homes come out so much [less efficient] when you measure by housing unit or bedroom; it's because they are superfluous in the things that they provide for the people who live there, both by global and historical standards. Even if you're saying we want to achieve for everyone the type of upper-middle class lifestyle of people in the 1950s, what we're building now is just way beyond that. We want people to have starter homes [at a similar scale to] our parents' generation or their parents' generation, but part of the reason [houses] are so expensive is because they're just so massive.

MP:

What do you think the role of regulation is in limiting embodied carbon? Especially since we already have the TGS or various other municipal codes that look at operational carbon.

SS:

There are many different approaches to this type of regulation, for

example, it can be fee based or tax based, right? We could say right above a certain size, taxation rates go up so that you're taxed per square meter and above [a defined] area basis, your tax rates start to go up. I think that would be a reasonable approach. The carbon tax should already start to do this as it gets higher, impacting material costs, which will incentivize us to build more efficiently and design better even if the units themselves don't get smaller. For example, in a double loaded corridor you often use like 15% of the floor plates for hallways and that's not even counting the hallways within the unit. If you design a single stair, you're down to 6% and on top of that there's less hallway within the unit. So now we can build exactly the same amount of floor area, but deliver either more housing or bigger units.

At the same time, single-family homes often have underground garages, or very big garages, or very big basements. We could design less space for cars and more space for people. We could have less space underground and more space for people. It doesn't have to be a masochistic [endeavour], where we make everything harder and less pleasurable. It could be that we design better to use our resources for the things we really want.

I think that another approach to the regulatory environment could be to put a cap on the per unit amount of GHG [emissions], so that a one bedroom gets some amount, a two-bedroom gets a bit more, and a three bedroom gets a bit more. Although any metric can be hacked, so there's no easy way to write a perfect regulation, but I would like to see us have a conversation about a GHG budget. In the UK they have the GHG budget for the entire economy, and that includes construction. I think if we're serious about climate, that's the type of thing we need.

MP:

Is there anything that's missing from this conversation, either this literal one or the broader metaphorical one? What future research do you think is most pressing?

SS:

I think we don't talk enough about efficient use of resources. The conversation is too dominated by what technology or what magic

material can we slot in that lets us do everything the way we're currently doing it, but fixes the problem. Electric cars are a version of that; couldn't we just slot in electric cars and then wouldn't automobility be fine? Couldn't we just use wood and then all construction would be fine? There is a lot value from those types of switches, but they also are not enough. They're often miles away from enough and sometimes they don't even make it better since we get fixated on the technology. You can have a really sustainable wood building and you can have a really sustainable concrete building. Focusing on [the question of] "couldn't we just switch to wood?" misses the fact that you can just design concrete buildings really well.

We're not talking about any sort of resource efficiency. How do we use our land to deliver the things we want it to? How do we deliver high quality public space as part of making a community that people actually want to live in? All of this stuff about how could we design efficiently so that we're using our materials well, we're missing that conversation.

Generally, people want totally different outcomes [than we currently have], but want to have all the inputs remain the same. That's the conversation that I have a lot.

The way in which I encounter fire safety is people using it as an excuse to design badly. And it's not just fire safety, it's all safety; we need really wide roads because our fire trucks are big. [Why don't we] get smaller fire trucks? We can't build more units because fire this or fire that. Fire is a very real way that people get hurt and we need to take fire safety seriously, but so are all the other things. [Building] roads that are too wide is a real thing that kills people too. Not having enough housing available is a real thing that leads to massive negative societal consequences. Increasing our consumption and pollution is a really bad thing. That's the way in which things like fire safety or other things that are like safety come up. We protect for certain kinds of well-being but not others.

Interview with Conrad Speckert

MP:

Can you just give me your name and tell me a little bit about yourself?

CS:

Sure. My name's Conrad Speckert and I'm an intern architect at LGA Architectural Partners in Toronto, who also designed the building you're in. As for my background, I have worked for various architects in Canada, Europe and Asia. When I went to McGill [University] to do my Masters thesis, I did it on the building code requirement for two exit stairs and afterwards worked on developing an actual code change request with David Hine P.Eng, [who is] a very good building code consultant and fire engineer.

We submitted that to the National Codes Board, CBHCC, which has reviewed, prioritized and will be developing that code change for the 2025-2030 code cycle. We've also met with the provincial ministries in Ontario, BC and Quebec, and they have started consultations on this topic with fire safety experts in each province. Since then, it's been interesting to go down the rabbit hole of building code discussions with architects, a reminder that so much of our time and energy is spent with building code.

And yet, in architecture schools, it's well… When I started doing my [thesis] work, I received the comment from one of the professors that it wasn't an appropriate architecture thesis. He said: "If you want to look at staircases, please design a beautiful staircase." I would like to think now, seeing how meaningful it has been, it hopefully encourages architecture students to think more like engineers, less like artists and poets, and to embrace a study of technical codes.

MP:

So you've been researching about five years now, is that right?

CS:

Oh, don't age me that much. This [work] started in 2020 so it's been

about four years.

MP:

You've been looking primarily at single stairs, have you looked at the impact of other code changes in some depth?

CS:

So, the other scope of work I have been part of, not about building code, but looking at zoning reform, specifically for multiplexes. I was a project manager in phase 1 of Rehousing, a collaboration with the University of Toronto, where we looked at the City of Toronto at the same time as their planning department was considering permissions for four-unit multiplexes. We helped them visualize what that could be architecturally, and then wrote a kind of consultants' report on things like floor space index, building height and setbacks to help inform their zoning bylaw through actual case studies.

In other discussions, we're now working on a pilot project that's been funded by CMHC because our building code has prescriptive, acceptable solutions in Division B, but it also has a structure that says you can do alternative solutions where you demonstrate that you have an innovative solution that meets the same minimum levels of safety or performance. So what that means, is that an architect can design a single stair building and show that they have done other things to make that single stair building meet the same level of safety as a baseline building with two stairs.

For instance, if a three-story building with two stairs doesn't need sprinklers, and you design a one stair building with sprinklers, you could work with a fire protection engineer to demonstrate that you have met at least the same or better level of safety, compared to the minimum requirements of the prescriptive building code. We're now working with 10 Architects across the country to build 10 pilot projects. There have been a lot of meetings where we talk about building code and it opens up a discussion around innovation that is goes well beyond just single stair [requirements].

One of the things is around the size of elevators and elevator technical requirements in North America which are much more stringent than they are in the rest of the world. The rest of the world essentially has a harmonized standard, except for Japan, which means that if you're an elevator manufacturer, you've got this broad

market which reduces cost, time, and availability. North America and Japan are sort of weird regulatory islands.

The other big one that there's been a lot of discussion about is the spatial separation of buildings, which is the side wall construction that you're allowed to do. Section 9.10.14. of the building code deals with spatial separation of buildings [other than houses] and 9.10.15. is spatial separation of houses. A house is defined as a building with not more than two units, so a two-unit building is allowed to do certain things that a three-unit building or four-unit building cannot.

Now of course, the spatial separation of buildings is also for non-residential uses of small buildings. So, a warehouse stacked full of plywood requires the same spatial separation as three-unit house. This is to say that we've created these trigger levels, but there's a clear exemption for two-unit houses – which is the same as in the International Building Code. There's the IRC, the International Residential Code for one- and two-unit buildings, and then everything else [must comply with] this other, significantly more restrictive code.

That is why in North America we see mostly houses and stacked townhouses - because they're all using the house definition to carve themselves out of having to do a whole bunch of other things. And I think, yes, maybe a three-unit building has a higher fire risk than a two-unit building in the sense that it contains more fire load, i.e. one additional kitchen. But the incremental additional safety requirements that come with three units are vastly [disproportionate], the scale jump is way more severe than you would think makes sense.

Spatial separation of buildings is a nuance where you then have to make the side walls non-combustible, and that's a bit awkward because you can do non-combustible construction as concrete, but you can also do it as steel studs with spray foam in between. If you do a fire test on a steel stud wall and you do a fire test on a wood frame wall with wood fiber installation or with mineral wool insulation between the [studs], the wood frame wall will beat the performance of the steel.

What has happened, and architects have complained about this, is that rather than having two different trades, two different contractors come on site because they want to do the floor assemblies and the interior wall assemblies out of wood but then have to re-engineer for two steel stud walls along the property line - the two Long walls

- because in Canada, lots are typically less wide than they are deep. They just say **** it, we're going to build a steel building. From a carbon perspective, that's disgusting, from a cost perspective and availability of trades perspective that's limiting, and if the fire performance of a wood beats the steel stud wall, then I would like to ask those architects, why are you being lazy? Why are you not going for an alternative solution to meet the performance? Often, they're just on a timeline or they are too ignorant to know that [an alternative solution] is available to them.

There are other things too, like in the Vancouver Building By-law, when you look at unprotected openings in their code, you can put wired glass, glass block, or you can sprinkler the window as a way so that the window is no longer defined as an unprotected opening. It's now a protected closure. In Ontario's code and in the national model code, sprinkler protection hasn't been added as an acceptable solution, and so every time an architect runs into this, which happens a lot, they have to do the engineering report, pay the alternative solution fee, and delay the project timeline, to get the sprinklered protected opening approved. Since they're being accepted left, right, and center, I don't see why the code has yet to adopt sprinkler protection of unprotected openings.

Fire chiefs have pointed out that if a fire occurs and a sprinkler system activates and the fire is suppressed, or the fire department extinguishes it, then the fire sprinkler system is down and it needs maintenance before it can be operational again. So, there's a period of time in which the sprinkler system is not functional and that creates an additional risk during that time period. I don't think the rationale that for a few days or week after a fire event occurs, one of the mitigating measures is down, is a rationale to not allow for it as a measure in the first place. I think that our fire codes should simply address what to do during that week. And if that comes with additional maintenance and operational measures, that's something that the regulations can figure out. There's a bit of the chicken before the egg issue in a lot of our codes which is perhaps why we don't do the smart thing.

Those are the big ones: elevators, spatial separation, sprinkler protection. From a carbon and cost of housing perspective those are the ones that I keep hearing about.

MP:

You talked about a lot of things there, so let's circle back to the to the topic of regulation and building form. You talked about some of the reasons that we see stacked townhouses and the double-loaded corridor form. Are there nuances to this? Or other examples where a dominant building typology is a direct result of a regulation?

CS:

Definitely. If you go out to the metro-burbs; Markham, Richmond Hill, for instance, you'll see a ton of these townhouses in a row. They are built to be exactly the maximum of 600 square meters. Then they'll build a firewall and repeat it. The whole basis of this is [that 600 square meters is] the absolute maximum you can do in Part 9 without hiring an architect.

These are massive pieces of land that could get cut up in any particular way, but because of this reason, they are cut up in exactly 600 square meter building area chunks. If you drive by, you'll see the kind of ugly roof details, right where the firewall separation is. All of it is because the companies building these wanted to do them in a way that wouldn't require them to be in Part 3, but to max out the Part 9 restrictions. So that's one example of building form directly derived from code thresholds.

There are the high building requirements of our code in 3.2.6., which come into effect at 18 meters, and some people have said that they're a bit weird because it means that if you build a building at 19 meters or at 90 meters, the trigger levels are similar. Certain things scale; there's another jump at 36 meters and the systems scale to a certain degree. If you have to pressurize a [vertical] shaft, and the shaft is 7 floors or the shaft is 70 floors, the calculation and equipment size is vastly different. Generally speaking, the biggest [jump in scale] is the firefighter elevator, which needs backup power supply provided by a generator.

Personally, I like low- and mid-rise buildings, so if there are code requirements that penalize things over six stories, I don't have personally have a problem with that. It does mean that we don't see a lot of seven and eight story buildings because developers look to get the economies of scale back for the high building requirements. Now the degree to which that really impacts project feasibility, I don't know. I just think that it might be worth looking at whether the high building requirements should be kicking in at exactly 18 meters or some of them at 18 meters, some of them at the 24 or 36, etcetera.

MP:

That threshold limit is one of the things I'm looking at right now, where six-storey combustible buildings have an absolute height limit of 18 meters whereas the a six-storey non-combustible building is only limited by stories. Similarly, the first storey is defined from the floor that is not more than two meters above grade, which means we're getting these six story buildings plus basement as opposed to a 7 storey with no basement, which present very similar fire risks.

CS:

The basic Fire Department fire truck has an aerial apparatus with a 75-foot ladder (22.9 m), and that's not so much about being able to rescue people, but it's about being able to go up there with the hose and be able to spray water on any given part of the building, which makes sense to me.

And you know, Canada has figured out a way to do wood buildings over six stories, and it's mass timber and mass timber is great. I'm not sure that fighting for a world in which we can build wood frame at seven or eight stories is worth the time and effort because we can just switch to mass timber at that point. It's a bit of an arbitrary trigger level, should it really be six or should it be seven? Or should it be defined in meters or should it be some sort of performance metric to the fire department?

But again, with this scale of projects, you often just don't want to have to go through the engineering reports, and consulting, and the "this fire department has this truck but that one's going to get decommissioned soon because our municipalities shrinking", or whatever the narrative is. Sometimes we push back on prescriptive codes because they seem frustrating, but at the same time, they actually make our lives easier, because if you look at some jurisdictions that only have performance-based code, it can be extremely laborious and confusing to navigate. I think the perfect world is one in which we have a prescriptive code and a performance-based code side-by-side, and you choose at the start of the project which one are you going to work with. If you've got a simple project, a tight timeline, and a low budget, you do the prescriptive option. If you are doing an airport and you've got every consultant and a massive budget for it, you go performance-based.

Maybe if we did eventually write a performance-based dual building

code, we could make the wood frame, and the high building requirements, and everything else have a kind of holistic scaling system. But I'm not too critical of our prescriptive code having strict trigger levels - I just think some of them are really awkward.

MP:

Can you talk a little bit about the challenges in response to your code change and the kind of the wicked problem that you talked about your research?

CS:

The first challenge was demonstrating why it matters. The industry has been doing things a certain way for a long time, and while many people have traveled to other places and have seen how it's done in another other way, many haven't. So, the first point was to demonstrate why this matters and what the outcome would be if it changed. Then it's about addressing every single nuanced critique or concern that the people critiquing it might have – even if it's a completely irrational thing. I've been told "well, what about in an active shooter situation? What about the risk of intruders?" When we look at our code, the first objective in the code is fire and life safety. And of course, the part where it says emergencies, there's a note in the appendix that says emergencies are defined more broadly than fires such as seismic events, risk of intruders, etcetera. Then we then had to think, if emergencies are defined more broadly, that's an important point. We had mostly focused on aspects around fire safety and single stair because that seems to be the biggest concern, but what performance metrics are there in the code for risk of intruders? How can we make our single stair buildings have a higher level of safety against risk of intruders than conventional code? Down in the States where people are working on this, they're being asked to show how single stair has a reduced risk in active shooter situations, which is insane because these are like 20-unit residential buildings. We shouldn't have to have that discussion, but that's to say that if you can address every single concern that someone who doesn't like it would have on day one of the conversation, that is extremely helpful.

You then have to look at the costs and the benefits and be really, really thorough on putting yourself in the shoes of the other perspective. For single stair, we've been working on this for three years, having conversations with architects, planners, building officials, fire chiefs,

fire engineers, and regulators and so we've gotten a lot of practice.

MP:

And so wicked problems are about the multi-faceted concerns that drive any sort of decision like that?

CS:

Yeah, I think wicked problems just means when you have to do inception; when you have to go "here's the problem, it's based off of this, which is based off of that, which is based off of firefighting and risk levels from 100 years ago, which is based off of fire truck reach, which is based off of this." And then there's just a general cultural apprehension to anything that would encourage small apartment buildings, especially if you're someone who fetishizes that we should all live in a house with a white picket fence. It's a wicked problem when it is that multi-dimensional.

MP:

You've talked about equivalent levels of safety a couple of times and I was wondering if you could talk about how we quantify this in practice?

CS:

Yeah, that's a tricky thing to do, because in our code we have the acceptable solutions and we have the objective statements. There are also the intent statements, though you have to really go digging for them. If you look at the intent statement for two exits, it talks about them being about redundancy. This is part of the issue with quantitative analysis; some fire engineers have said, "well, we could show that if we model a fire starting in a kitchen the way it would spread and we would do sort of multi level analysis."

Fires most often start in the dwelling unit, where there's a sprinkler system. If the fire sprinkler system succeeds, it suppresses the fire. The sprinkler system notifies the fire alarm system which is automatically monitored in some cases, the fire department responds, great. So that's one fire scenario. Scenario two: The sprinkler system fails, but the fire alarm system goes off. The fire spreads around the unit, but the doors are upgraded and so by the time the fire department arrives, it's been addressed.

OK, now the fire alarm system fails. The sprinkler system fails and

the door was left open or didn't close properly. How far can the fire spread and how much time does the fire department have to arrive to scene? You can do this multi-level tree and basically show how six levels of redundancy have this result for two stairs and this result for one stair. That's a sort of quantifiable method.

Then you could do a different fire scenario. What if there's a fire in a staircase? If you've got two staircases, you've got the other one, but if you do things to make that single staircase have a lower risk of a fire in it than either of two stairs, or you do things to reduce the risk of the fire spreading outside of the stair, or you sprinkler the landings in the stairs so that the fire won't spread within the stair. You provide a better level of safety.

So there's this sort of probabilistic modeling that can be done, but often the challenge is when there is a [requirement in the code] that hasn't been linked back to its underlying quantitative rationale. [Something that] was added in because of, you know, a discussion that occurred in the 1930s that was poorly documented. Then you're trying to quantitatively demonstrate you're achieving the same thing, but you don't clearly know why it is in there in the first place. And that can be challenging.

A townhouse only has a single exit within that larger dwelling unit and if the minimum level of safety we had to meet for a small apartment building with single exit was simply to be better than a stacked townhouse, that would be very, very easy. But that's of course not the argument we're talking about, the same scale of building.

It's really tricky. I think fire engineers are getting very good at this, but the other issue is: "is the authority having jurisdiction experienced, open minded and interested?" Oftentimes they just don't want to take on the complexity of it.

There's a system, I think somewhere in Scandinavia, where if you are an architect, you work with a fire engineer, you do an alternative solution report, you then get peer review done, not by one fire engineer but by two separate fire engineers, you're all qualified professionals, at that point the municipality can receive the application and doesn't need to take on any liability or risk for having accepted it. It basically says [that] enough of our country's experts, who know these requirements better than we would expect the municipal plans examiners to ever know it, have said this is OK, so we're comfortable with it. That is how structural engineering

works, when the structural engineer does their design, it's quite rare that the municipal plans examiner will say "no, your column hasn't been sized for enough wind load." It is trusted that the structural engineer as a qualified professional, with their professional liability, takes on having done that calculation correctly. So, a similar system should exist for an architect and a fire engineer to say that we have designed this building to meet the equivalent levels of safety. And you, as the municipality, can be comfortable with that because we've talked about this and looked at this carefully with enough other experts. That would be a great model that Canada could adapt.

MP:

Fantastic. Last question: is there anything that you think is missing from this conversation? Either literally or in a metaphorical sense.

CS:

The whole point of the code is to do what's in the public's best interests. It's directly in the public's best interest to ensure that fire safety is provided, but indirectly, it's also in the public's best interest to reduce embodied carbon emissions. You can start to look at embodied carbon in terms of lives lost and in terms of dollars that it costs, and compare that to our fire death, fatality, and injury rates. I think that's an exercise that you probably can't do in two or three months, but is a narrative piece to say that at a certain point, if there's a way to build a combustible wall that meets the same performance as a non-combustible wall, then it is in the public's best interest that the wall is built that way.

If it's in the public's best interest to reduce embodied carbon and the amount of overall risk to all Canadians posed by embodied carbon exceeds that of fire safety, then we need to really think about it. The problem is that when someone dies in a fire, it goes in the media. It comes with visuals. It's very reactive and emotional. It's not like you can photograph embodied carbons impact on the population and write a Toronto Star article about it.

Interview with Beth Weckman

MP:

Can you give me a bio short about yourself?

BW:

Sure, I come from a pretty fundamental combustion background and got into fire safety when approached by the fire service in [Waterloo] who had seen my liquid pan fires with lasers and things going through them and felt that I could be of help to them. That started basically a 25-year partnership with the fire departments in this area. Out of which came the fire research facility and the fire safety program. Most of my research from then on has related to fire safety.

[My research is concerned with] the fundamental science that should be feeding [the things] we're putting in codes or the calculation methods we're using. What are the test methods? What do they represent in terms of a real fire event? [Do the tests] scale from small all the way up to large scale fires?

MP:

Is most of your research derived from firefighter needs or does it work in parallel to them?

BW:

It's parallel, where you have [to address] the fire safety concerns of the engineering community, firefighters, and any other stakeholder insurance industries. They each have their own way of looking at fire safety, so the most fruitful way of educating people and or trying to interpret your results is to do multi-stakeholder assessments. We try to [provide] feedback information to the fire service in a format that is in their language, which is a different communication mode than how you would communicate to the building code industry or the even the fire testing industry.

Product manufacturers, each of them, speaks a different language and often even the same word is interpreted differently depending

upon whether [the audience is] a practitioner, a research scientist, or a fire service person.

The definitions aren't black and white; flashover is not a black and white phenomenon. It is understood differently. There are four technical definitions of it, a standard testing definition of it, a firefighter observational definition, (of how it takes place or what they look for just before it takes place), and one [written by the] person who tried to scientifically bring them all together. That is seven definitions, [and they] still aren't rectified. Even between civil and mechanical fire safety people [there are differences in language]; a fire safety person who's [from] the fluid [research] side would call [a fire] a fully developed fire when it's gone into steady burning which is a post flashover phenomenon (because flashover is the transition from early burning to full compartment involvement) whereas a civil engineer would start with full compartment involvement and look at things as all premixed. In one instance, you're [researching with the focus of] trying to get the people out, in the other instance, you're trying to keep the building standing. For the building to stand, the structure has to withstand a full room fire for a certain period of time and you don't want your doors, fire breaks, and whatever else to fail. But to a fluid mechanics person, the smoke's going to kill all the people [before that happens]; the smoke starts long before any compartment is fully involved.

Yes, [these considerations] are all accounted for in the code, but they come from quite different premises, background information, and often personal experience. So, when you try to bring them together into a fully fledged system design, it's really easy to miss a part of the system.

MP:

Going back a little bit to your research, how does it engage with the construction industry?

BW:

Through product manufacturers, through test standard work like ASTM and ISO, I sit on most of the committees as one of the Canadian technical experts, [and through] joint projects with institutions like the NRC. I haven't done anything directly with the codes, but certainly with other aspects that feed into them. Additionally, [I work with] any of the sort of related government

organizations that might be interested in fire safety perspectives in addition to the municipal fire service. We do a lot of work with the military as well, they have their own construction concerns and types of construction, like ships.

So, I don't sit on codes committees, but I do sit on the standards committees that set the thresholds of material performance or product performance for the codes.

MP:

Will technical committees make recommendations to the building code committees about which standards to use?

BW:

Yes, some people directly crossover into the building codes committees. However, when we look at research more broadly, I have students who are researching gaps in the building code [where] we're using fundamental fire safety and assessing building codes, which they'll then bring back to industry and presumably, into the code system. Materials performance can get into the code systems either through a manufacturer [with the] research we might do, or it could come in through a manufacturer [representative] who's sitting on the codes committee, or it could come through a connection between the standards [committee] and the codes [committee]. It's not a direct path, but the ongoing research points to either the gaps that we should consider or the positives of [confirming] that we are still [working with] a good set of assumptions.

MP:

Do you have specific examples of places where you think the current testing standards or the current application of those testing standards could be improved to better reflect the actual fire risk?

BW:

Testing standards do not reflect fire risk. Testing standards rank the performance of something - either a system or a material, more often [it's] a material than a system. They are only intended to rank things but over the years that I've been on the standards committees - we're all engineers, so we like numbers - people like to take a number out of a test standard that's intended to rank materials by whatever criteria, most smoke produced to least smoke produced or no smoke

produced for example, and [adopt] it as the threshold for design [since] it produces this amount of smoke. But that's not even close, because the smoke from a four inch piece of material and the smoke in a real fire don't connect.

MP:

Standards are only intended to evaluate materials relative to one another and not really to produce quantifiable data?

BW:

Correct. They don't use the right ignition sources, they don't use the right radiative flux, they bear no relation to a real fire scenario unless you're looking at custom design tests.

We certainly use the pieces of standard testing equipment in our lab. They're very convenient, but we also design custom tests where we try to actually capture the real fire exposures, which are typically mixed radiation and direct flame impingement of some kind. We spend a lot of time explaining to our partners and in research that no, we don't do a fire resistance rating test.

We don't have a furnace at the lab, because unless you're at the fully developed compartment fire stage [the temperatures prescribed are not reached] and even then, there is not a fire on this earth that has a uniform temperature exposure. I have a student who's researching a fully involved compartment fire, and it does not have a uniform temperature exposure on the wall, so if you want your product tested for a real fire, here's how we do our fire exposures, here's the gradient you get. You can see if your product is likely to breach because it doesn't do well in gradients. Gypsum is classic for being bad in temperature gradients. Investigators use gypsum fall off as a way to estimate the intensity of the fire.

MP:

Will manufacturers really invest in that sort of testing? Do they care about real fire scenarios and not "standard" fires?

BW:

Some of them are interested in actually how their products perform. In the end, they have to pass the standard fires, so we also do that within the lab. We've developed a bit of an expertise in interpreting the tests that we do and how something might perform in a larger scale test or situation. There aren't a lot of labs or a lot of people

around with that kind of experience, and that's sort of where the system breaks down. I'm not trying to toot my own horn by saying that, but it's something that I've learned over the years. Back to when I started, I wouldn't even try to answer somebody's question like that because I knew I didn't know.

But now I will try to help people interpret [test results] because we have a much better idea in our lab of how you get from a cone calorimeter to a Steiner Tunnel to a full-scale fire test or a full scale fire. The people that we've done a lot of research with are industries who are interested in refining their material for fire safety. Typically, they have a matrix of different options - different amounts of fire retardant or particulates or various things - and they're trying to find the best one to start with, or they've failed some tests and want to do smaller scale studies to better understand how to pass the test the next time. There are some companies who, notoriously, engineer to pass the test which has led to large failures.

MP:

Can you describe what the difference between flame spread rating, fire resistance rating and combustibility is? What are their roles and how do they interact?

BW:

Combustibility is a that's probably one of the hot most hotly debated test methods currently. Half of the industry wants to call it noncombustibility and the other half wants to call it combustibility, because there are different inferences depending upon what the name is, even though they're all talking about the same test standard.

It's in the name and definition, right? I don't know the history in depth, so I hesitate to delve too far in, but the intent of the test is to define combustible versus non combustible construction. Classically this is done with a tube furnace and two thermal couples, but there are some materials which are going to fail, even though that they're not going to partake in a fire to any great extent. Mineral wool insulation is an example of this; as soon as it starts to heat, it insulates itself, and then you get the binder oxidizing inside, even though there's such a small proportion of it, only 3%-6%, it fails because of the way the test standard thresholds are set. Never in a million years is the test going to change, since some of the other products have been engineered to pass that particular test so they can be classified

as noncombustible.

MP:

There's also the material assembly perspective on it where a single material is never exposed to fire on its own, for example with straw bale walls, you would never just have exposed straw bale, it always comes with the layer of plaster.

BW:

Correct. And that's why in the code we have encapsulated mass timber construction (EMTC), not MTC, because MTC is clearly combustible, even if it self extinguishes. That is a direct result of the test standard, and this relates to the flame spread rating as well; if at any time during the test "X" happens, then the material fails. They do not account for materials that may recover some properties. I'm not suggesting that I would count on mass timber self extinguishing as my fire safety stop gap, but that's the sort of issue with the testing. There are other situations where materials will fail the flame spread rating test because [the test measures] the point of furthest advance of the fire, even if it only damages itself as the flame regresses backwards, you have to take that top point. Whereas another material will get to [the same] point [in the test] without anything left of the material, [these two materials] are going to have the same flame spread rating.

Testing standards are intended to derive a relative ranking, but each test method is designed for a particular set of materials. The Steiner Tunnel which measures flame spread rating, is the classic example of this. It is one of the most misused test standards because people keep extending it since it's in the code. You get this vicious cycle where something gets into the code for quite a reasonable purpose and then it gets extrapolated for another purpose [for which it was never intended]. In the case of the Steiner Tunnel, it was designed to mimic the wood coverings at the Coconut Grove nightclub fire. People went to a lot of trouble designing something that gave them the relative ranking, that reflected the fire situation. But then, over time, people have put in pipe sections, they put in loosely held insulation in cages. The test standard must have 29 appendices of different ways of mounting things that should never be mounted for testing in the tunnel in the first place.

So, when you ask me about what is a flame spread rating, it's how quickly flame spreads across a surface relative to red oak. To compare foam to red oak, or a pipe to red oak, and think that there

is a meaningful comparison, you have to be a little screwy, right? What are we comparing?

And it's not just some red oak, it was the red oak that happened to be 100 years old at the time that the test was developed. Now the density and composition of red oak has changed so they no longer measure smoke using red oak, and that should tell you something about the flame spread rating part. I actually had a really interesting case just recently where a product passed the Steiner Tunnel test, then [a testing agency] changed their Steiner Tunnel out for an improved design and it failed. So I looked at some of the parameters in the test reports and the test was still within spec, but I could tell them exactly what happened because they had pictures. And I won't tell you what exactly what happened, but the pictures said it all; that test is extremely sensitive to many parameters.

MP:

This also brings up the issue of where codes decide to draw the line in the sand, where 150 is too much but 149 is okay.

BW:

Yes, exactly.

Some of those categories are based on full scale performance of the material in practice, but that changes over time because we now have sprinklers, among other measures. If your fire safety system or fire protection measures within the construction industry change over time, then your baseline is a little bit off. And we won't pick up on it necessarily if another safety system kicks in and prevents the fire from doing what it might have in the historical scenario. We don't have a way of separating that out to relate back to the test standard that we might be using to specify in the building code.

You can go into the fire resistance rating as well and ask how realistic a constant temperature exposure is relative to the materials that are being tested and their anticipated performance in something that is not a uniform temperature exposure. Maybe in many situations you don't notice that non-uniformity because if it is fully involved, the temperature difference is small, but early in the fire, the print of the fire on that material is causing much higher temperatures from radiation, so the footprint is a much larger delta T. Then will the material still hold up [in the same way the testing suggests]?

MP:

Some of the literature that I've been reading has suggested that the temperature curve used for the fire resistance rating test underestimates what a real fire might present.

BW:

It doesn't follow a real fire at all. There's the time equivalence method, where you look at the test results for a material and a real fire scenario in order to bring the two together by integrating the total energy under the curve, which is not a bad theoretical or conceptual framework. But will your material really do that? What evidence is there that the that the materials actually going to behave that way when the whole curve is a different shape because you can prove that many materials are very sensitive to the transient way they're heated.

MP:

Is there anything else on the limitation side that we haven't touched upon?

BW:

I mentioned it with respect to the Steiner Tunnel, but as materials evolve as we tend to adopt these new materials, and what's to say that any of [our current] test standards are appropriate from a fire safety point of view? We should be looking at systems, and straw bale construction would come into that category.

Typically, we specify the way of mounting the material in a standardized test system, rather than putting the system together and testing it as it would be in use. Even if we tested it as it would be put together in use, what is the quality of real construction versus the quality of the test lab? Although, who's to say which would be better, I've heard stories on both sides of that one. With things like gypsum that have very specific mounting procedures. You need screws this far apart in this pattern for this kind of mounting and interestingly, it's different if you're mounting a board horizontally or vertically – which speaks to the fact that the material is not 100% homogeneous under fire.

MP:

I was just reading this report by R.S. Ferguson about the problem of noncombustibility where he writes that in the past we knew what

was noncombustible and what was combustible, but new materials might have a mix of both. In his example, one of the new materials was paper faced gypsum. It talks about the limitations of treating things as single materials, when they're really just one layer of a much bigger system, that the combustibility test narrows to just two categories.

BW:

I often jokingly say that if something has hydrocarbons in it, it's going to burn. So let me throw something into your example, I have yet to see a gypsum wall. What do we put on top of the gypsum?

MP:

Paint.

BW:

Do you figure that burns?

MP:

Certainly.

BW:

We did some interesting studies with the Canadian Navy and I know the Ontario Fire Marshalls have done some interesting investigations about how important the thickness of the paint layers are. The paint is separately fire rated, so if we put it on a fire rated gypsum wall, we should be fire rated. Then we'll just build the paint up into legacy which can get quite thick and age it for X amount of time (in the case of a ship out in the sun).

I'm just commenting at the systems concept. No material is just a single material, they are all composites. There have been some very unfortunate fires in rental facilities because of the thickness of the paint on the walls. What do people do to spruce up their home? The same thing the Navy does on the ship to spruce it up when they have a visitor. Will those [layers of paint] partake in the fire? Absolutely. Is there any rule, regulation or anything else that governs this use? Perhaps under the renovation part of the code, yet it's standard use of the material. We don't think of that combination of things as a system, but it has real fire implications.

MP:

Can you talk about the relationship between scientific and experiential perspectives on fire safety?

BW:

There's a couple of things that I think should be noted. One is that, until very, very, very recently, I believe the last code cycle, the fact that the fire service would play a role during a fire was given extremely limited attention in the code. It was written in a way that said you can't expect fire service interaction before 30 minutes into an event [Note A-3.1.2.]. This note meant that people kind of forgot that the fire service existed. If you speak to firefighters about buildings where they can't get their fire trucks close enough or some of their other bones of contention, they're actually real and they impact their ability to service a building. There are a lot of things that are missing [from the code] that directly impact their ability to respond the way they should be responding because they're not considered as part of that system of fire safety protocols.

MP:

Which both negatively affects the firefighters and kind of overengineers the fire safety of the building because we're saying it has to withstand everything without the fire department.

BW:

That's one way of looking at it, but the other way of looking at it is: if we're giving them their due credit for emergency response, we should consider them in the equation and ensure that our roads are designed around our buildings or that there's alternative access or that the sprinklers and standpipes are in a reasonable position for them. [This approach] extends all the way to fire safety often being the final stage of design when [designers] are just trying to get the systems in when everything else is set in stone. The chance of [firefighters] not being able to do their job increases because [fire safety] is rarely considered before the final point in design. In my mind, fire service operation should be explicitly discussed or taught in the context of building fire safety.

MP:

As an aside, your talk to our [graduate professional practice] class in the spring is the only real mention of fire safety in my architecture schooling, which is absurd.

BW:

Thank you for saying that. I will touch on that a bit later, but that's why I want you to read the Grenfell Tower Report. They explicitly state that fire safety should be a certified professional activity, and if it had been, much of what happened would probably not have occurred. There are some other tidbits in there about test standards and companies being able to design to the test.

So where were we?

So that is one side of the fire service; the fact that they're not explicitly included in the education or code system. They're in the room so they have a say, but along that line [is the fact] that fire statistics don't form a major role in how we make our design. Our next code cycle has a controversial decision: the single stair. [I'm] not saying one way or another, but let's look at the statistics. Has blocked staircases been a problem? If they have been a problem, under what circumstances [did they occur] and further are those circumstances likely to happen [under the proposed regulation]? If the answer to all of that is yes, let's not do that. There may be other issues as well, but [blocked staircases] are the kind of thing that we don't have good information on. If it's important to us, should we not work with the fire service to collect the right information? Which is again where the fire service part of the equation has dropped out.

Another side of [the issue of research versus experience] is that engineers lack of any concept of what a firefighter has to do, of procedures and how they actually fight a fire. We're putting people through fire gases right now as part of another research project and people's first responses are "Oh my God, I never want to be in a fire." But we're sending these [firefighters] in, not on a daily basis, but on a fairly regular basis, without any appreciation in our design. We worry about the aesthetics, functionality, and everything else, but we don't necessarily take into account the decision-making processes [that occur in a fire]. This could mean occupant responses or fire service responses, but are there elements of the design that should be modified or should be codified with this kind of considerations?

We're finding that something as simple as how door handles actually open can have a significant impact. Can a person who is cognitively declining, inhaling smoke, and whose eyes are burning operate the door handle? Similarly, we don't know that much about how glass breaks because it depends upon how it's installed, and this has a large impact on ventilation rates in fires. Continuing on

to energy efficiency, the energy code is totally disconnected from the building code even though changing all kinds of things in it will have huge fire safety implications [like how fire reacts in an airtight compartment relative to an older, leaky one]. Yet somehow, energy doesn't connect to fire in our minds.

MP:

That leads us nicely into the final question: what research do you think is most pressing?

BW:

I think we need a steady underpinning of research.

I think we have to take one step back from incident-based research and [identify] that these are new technologies or new changes, but that's going to happen all the time. If we design our research to catch up to the next new change, we have a problem, right? We're always going to be behind. The question is: how do we take a more proactive outlook on the issues?

And I would say you could say this for safety in general, how many times in your education and maybe this isn't fair in architecture, it would certainly be very appropriate and Engineering, have you heard a discussion about risk?

MP:

In architecture school: never.

BW:

Engineering is pretty much the same. The premise of all of our codes is risk avoidance and minimizing acceptable risk. So here we are, training professionals to minimize risk without learning about how to assess risk. It's hard because there's not really a baseline risk. It's always going be a consensus baseline and we pretty much have to accept that [the baseline] is going to stay a grey area because of public perception and all kinds of other things.

So, the communication of risks becomes important, and that's another area that right now we don't do well. People see timber buildings going up in flame and think that timber is bad so we shouldn't be building with it. But let's look at the benefits and the risks of it, [and consider] how we weigh those off against one another. How do

we set up a system where we can carry out that discussion? We're missing all of that [right now]. To me, one of the big research areas is how we can build risk frameworks.

We've been looking at community risk [by evaluating] house fire risks in vulnerable communities, and we could tie it technically to major repairs needed in those communities when everybody else is tying it to socio demographics. Take public housing as an example: how well maintained are most social housing developments after a period of time? Very poorly, so we [blame it] on sociodemographics – that those people don't behave "properly" or whatever we want to use as our norms. Instead, let's think about how many of them is maintenance the issue? How many have landlords or custodians that are upkeeping those facilities? How many are built to be easy to maintain? Were they built to a standard that anticipates that everybody is going to have the money to go out to Home Hardware? There is tons of research on why smoke detector programs don't necessarily address some of the major needs well, because there's a piece of gold in a smoke detector when you don't have much money called a battery.

Then you go back to the fire service trying to do the public education campaigns on fire safety, but maybe they should be campaigning on maintaining your home. Or maybe we should be looking at how we build things so that people feel they have ownership of them rather than [patting ourselves on the back] saying "we're so nice, we gave you this social housing" even though you don't really want to live in it. On the way to the fire lab we have the [Urbs Road] tiny homes project, and it's really interesting to see how the different people have put a plant outside their front door. Every time I drive past, I look into the yard to see who's done what, what's appeared, and you can see the [homes] where it's obviously meant a huge amount to somebody.

There's a whole spectrum of research in this area which is all interdisciplinary, and that's where the difficulty for a lot of researchers starts. Many of my projects are across disciplines and you're communicating with people in a different language than you're used to speaking. I would argue that my research with the fire service is interdisciplinary, but people don't look at it that way, our system doesn't look at it that way. When you get into fire safety with all its different stakeholders and perspectives, it has to be addressed in [an interdisciplinary] way.

The other thing, aside from the primary research, is education, and I

think you just spoke to that with your experience [that the building code is not taught in architecture school]. I think it's of paramount importance that we start educating students about [the fundamental parts of the code] - the code can only be as successful as how well the people are educated to apply it. Very few people actually understand what a fire is or what firefighters are facing when they fight a fire. How can you if you don't have any education about fire dynamics? How can you connect a potential deficiency or weak point in the codified version of a design to what might happen? I'm not suggesting anybody is wrong about just applying the code, but we're relying on that code to do an awful lot, when in reality it's pretty specifically defined for square boxes of design from square boxes of information.

MP:

So we need to further integrate fire research into practice and make sure that these two fields are reflective of one another.

BW:

That's right, but to do that, you need people trained in the fire side of things. It doesn't have to be everybody but I'm sure there's a group that [the fire training] would be quite appealing to. The Grenfell Tower Report says that there need to be people trained or cross trained to understand the fire safety inside the code.

MP:

And these professionals certainly need to be more integrated into the design practice, because this role is currently fulfilled with fire engineers but they're still outside consultants.

BW:

Yes, they're not a part of the design team from the beginning and there's research about that being an issue. It's one of the biggest limitations but it's difficult to codify, and I'm not sure that's [an] appropriate [solution] because there are some standard building types where you don't really need anything more than a good sprinkler system. Then there are others which you [cannot design safely] if the person doesn't have the training and the background. How does [the code] decide when that threshold is met?

Appendix B

Barrier #1: Access Routes
Average Road Width

Austria	Vienna	6.6	0.22
Belarus	Gomel	6.5	0.26
Belgium	Antwerp	7.1	0.21
France	Le Mans	5.5	0.34
	Paris	6.2	0.28
Germany	Berlin	8.8	0.17
	Halle	5.0	0.40
	Oldenburg	6.6	0.24
Greece	Thessaloniki	7.0	0.23
Hungary	Budapest	7.7	0.15
Italy	Milan	5.0	0.40
	Palermo	5.4	0.39
Japan	Fukuoka	5.1	0.46
	Okayama	4.4	0.61
	Osaka	5.5	0.40
	Tokyo	5.0	0.51
	Yamaguchi	5.8	0.45
Lithuania	Kaunas	5.4	0.31
Netherlands	Zwolle	6.6	0.34
Poland	Warsaw	6.3	0.24
Russia	Astrakhan	5.3	0.29
	Berezniki	6.0	0.36
	Dzerzhinsk	5.2	0.31
	Moscow	5.6	0.32
	Saint Petersburg	8.1	0.20
	Tyumen	6.7	0.20
Serbia	Belgrade	5.7	0.37
Spain	Madrid	11.3	0.22
Switzerland	Lausanne	6.2	0.21
Ukraine	Nikolaev	5.6	0.26
	Rovno	5.8	0.34
United Kingdom	London	7.5	0.18
	Manchester	6.3	0.35
	Sheffield	7.5	0.24
Australia	Sydney	9.9	0.08
Canada	Montreal	16.1	0.12
	Victoria	7.3	0.22

New Zealand	Auckland	10.3	0.20
United States	Chicago	10.0	0.27
	Cleveland	21.8	0.13
	Gainesville	9.9	0.13
	Houston	10.0	0.12
	Killeen	18.8	0.13
	Los Angeles	15.8	0.18
	Minneapolis	8.8	0.16
	Modesto	10.2	0.22
	New York	8.9	0.14
	Philadelphia	8.1	0.15
	Portland	10.0	0.10
	Raleigh	9.5	0.13
	Springfield	7.9	0.13
	Toledo	9.3	0.14

Barrier #1: Access Routes
Road Composition

MATERIAL	QUANTITY	QTY_ TYPE	TRANSPORT DISTANCE_ KM	SERVICE LIFE	WASTE SHARE INUSE PHASE	EOLPROCESSID
Flexible Arterial	1	m2				
Asphalt pavement (asphalt concrete) surface course (wear layer), hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.04	m3	50.0	30.0	0	asphaltRecyclingEOL
Asphalt pavement (asphalt concrete) binder course, hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.19	m3	50.0	30.0	0	asphaltRecyclingEOL
Aggregate (crushed gravel), generic, dry bulk density, 1600 kg/m3	0.05	m3	30.0	-1.0	0	donothing
Aggregate (crushed gravel), generic, dry bulk density, 1600 kg/m3	0.35	m3	30.0	-1.0	0	donothing
Geotextile, generic, 312 g/m2 (1.02 oz/ft2), Composition: PP net, non-woven PE felt	1	m2	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Flexible Local	1	m2				
Asphalt pavement (asphalt concrete) surface course (wear layer), hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.04	m3	50.0	30.0	0	asphaltRecyclingEOL
Asphalt pavement (asphalt concrete) binder course, hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.06	m3	50.0	30.0	0	asphaltRecyclingEOL
Aggregate (crushed gravel), generic, dry bulk density, 1600 kg/m3	0.05	m3	30.0	-1.0	0	donothing
Aggregate (crushed gravel), generic, dry bulk density, 1600 kg/m3	0.25	m3	30.0	-1.0	0	donothing
Geotextile, generic, 312 g/m2 (1.02 oz/ft2), Composition: PP net, non-woven PE felt	1	m2	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Hybrid Arterial	1	m2				
Aggregate (crushed gravel), generic, dry bulk density, 1600 kg/m3	0.15	m3	30.0	-1.0	0	donothing
Geotextile, generic, 312 g/m2 (1.02 oz/ft2), Composition: PP net, non-woven PE felt	1	m2	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Asphalt pavement (asphalt concrete) surface course (wear layer), hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.04	m3	50	30.0	0	asphaltRecyclingEOL
Ready-mix concrete, Ontario industry average, 30 MPa concrete with air entrainment, 0.50 w/cm (F-1) GU (Concrete Ontario)	0.25	m3	200	-1.0	4	concrete300kgCement-ToAggregateEOL
Asphalt pavement (asphalt concrete) binder course, hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.05	m3	50	30.0	0	asphaltRecyclingEOL
Hybrid Local	1	m2				
Aggregate (crushed gravel), generic, dry bulk density, 1600 kg/m3	0.15	m3	30.0	-1.0	0	donothing
Geotextile, generic, 312 g/m2 (1.02 oz/ft2), Composition: PP net, non-woven PE felt	1	m2	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Asphalt pavement (asphalt concrete) surface course (wear layer), hot mix, 2330 kg/m3, 0% recycled bitmuen binder (One Click LCA)	0.05	m3	50	30.0	0	asphaltRecyclingEOL
Ready-mix concrete, Ontario industry average, 30 MPa concrete with air entrainment, 0.50 w/cm (F-1) GU (Concrete Ontario)	0.15	m3	200	-1.0	4	concrete300kgCement-ToAggregateEOL

Barrier #1: Access Routes
Road as Percent of Project

Road area (m2)	Emission Intensity (kgCO2e/m2)			
	29	79	60	127
15	435	11850	9000	1905
30	870	23700	18000	3810
60	1740	4740	3600	7620

	Project area	intensity	total bedrooms	house carbon	Road carbon	total project	% of project
Scenario Low Low	450	375	12	168750	870	169620	0.5%
Scenario Low High	450	375	13	168750	3480	172230	2.1%
Scenario High Low	450	375	12	168750	3810	172560	2.3%
Scenario High High	450	375	13	168750	15240	183990	9.0%

Barrier #1: Single Exit Stair
Death vs Stair Height

		Average fire deaths per			Single stair	Number of	
Country	Population (1,000 inh.)	Year	100,000 inh.	100 fires	Height	Career Firefighters	Career Firefighters per 100,000
Great Britain	63786	338	0.53	0.17	200	40100	62.866
Austria	8773	26	0.296	0.04	90	2775	31.631
Italy	61000	228	0.37	0.1	80	28870	47.328
Belarus	9492	625	6.59	9.35	75		0
Russia	146544	342	6.37	6.47	75		0
Germany	82218	393	0.48	0.22	60	34854	42.392
Ireland	4500	33	0.72	0.14	60	2012	44.711
Singapore	5612	2	0.04	0.05	60	2759	49.163
Finland	5474	72	1.32	0.58	55	3791	69.255
France	66628	300	0.45	0.1	50	54503	81.802
Sweden	10120	105	1.04	0.42	48	5051	49.911
Denmark	5756	67	1.16	0.49	45	1426	24.774
Romania	20121	382	1.9	1.31	31	25632	127.389
Spain	46570	165	0.35	0.13	28	-	-
New Zealand	4748	15	0.32	0.15	25	1719	36.205
Poland	38454	497	1.29	0.35	25	30349	78.923
Norway	5109	58	1.14	0.73	24	3718	72.774
Netherlands	17082	60	0.35	0.06	15.5	3145	18.411
India	1267500	19797	1.56	-	15	-	-
Japan	128130	1554.8	1.213	3.77	15	163693	127.755
USA	327167	3353	1.02	0.26	9	379900	116.118
Canada	35544	158	0.445	0.4	6	26000	73.149

Barrier #4: Building Height Definition
Marquette Wall Assemblies

MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM	TRANSPORTDISTANCETRACI_KM	SERVICELIFE	WASTESHAREINUSEPHASE	EOLPROCESSID
Foundation	1	m3					
Ready-mix concrete, Québec industry average, Baseline 35 MPa SCC with air entrainment (F- 1) (Association béton Québec (ABQ))	2400	kg	203.2	200	-1.0	4	concrete300kgCementToAggregateEOL
Reinforcement steel (rebar), generic, 60% recycled content, A615 (One Click LCA)	48	kg		580	-1.0	4.85	steelRecyclingEOL
XPS insulation panels, L=0.035 W/mK, R=2.85 m2K/W, 100 mm, 3.8 kg/m2, 38 kg/m3, compressive strength 500 kPa, 40% recycled polystyrene, CO2 blowing agent, Lambda=0.035 W/(m.K) (One Click LCA)	1	m2	100	350	-1.0	4	plasticBasedMaterialIncinerationEOL
W1 - Alum above	1	m2					
Alkyd emulsion-based paint, 1.2 kg/l, pigment volume concentration 15.8 v%, solvent weight 1 m% (One Click LCA)	0.000	m3		800.0	10.0	10	inertMaterialLandfillingEOL
Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft3)	1	m2	16	200.0	-1.0	12.5	gypsumRecyclingEOL
Polyethylene vapour barrier membrane, 0.15 mm, 0.14 kg/m2 (One Click LCA)	1	m2	0.15	350.0	30.0	10	plasticBasedMaterialIncinerationEOL
Fiberglass insulation in batts, unfaced, R-5.68 (Rsi=1 m2K/W), 1.381 kg/m2, Unfaced Fiberglass, Kraft Faced Fiberglass, Panel Deck FSK-25, FSK-25, ComfortTherm®, Cavity-SHIELD™ (Johns Manville)	4.48	kg		200.0	-1.0	8	inertMaterialLandfillingEOL
Wooden stud framing for drywall/gypsum plasterboard per sq. ft of wall area (incl. air gaps per m3), 2x6 in, 16 in spacing, headers incl. for 8 ft wall height (American Wood Council, Canadian Wood Council)	1	m2		560.0	-1.0	17.9	woodIncinerationEOL
Softwood plywood, 477.33 kg/m3 (Canadian Wood Council)	0.019	m3	127	560.0	-1.0	16.7	woodIncinerationEOL
Stone wool (mineral wool) insulation, unfaced, L = 0.0325 W/mK, R = 1 m2K/W, 32.5mm, 5.04 kg/m2, 155 kg/m3, (Range: 113-200kg/m3), 22% slag content, high pressure suitable (One Click LCA)	1	m2	50	200.0	-1.0	8	inertMaterialLandfillingEOL
Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)	0.004	m3		560.0	-1.0	17.9	woodIncinerationEOL
Air and water barrier system, mechanically fastened, 0.0451 lbs/ft2, 0.22 kg/m2, Tyvek (DuPont)	1	m2		350	30.0	10	plasticBasedMaterialIncinerationEOL
Roll formed aluminum cladding, 2.77 kg/m2 (Metal Construction Association)	1	m2		580	-1.0	7.5	aluminumRecyclingEOL
W3 - Brick below	1	m2					
Alkyd emulsion-based paint, 1.2 kg/l, pigment volume concentration 15.8 v%, solvent weight 1 m% (One Click LCA)	0.000	m3		800.0	10.0	10	inertMaterialLandfillingEOL
Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft3)	1	m2	16	200.0	-1.0	12.5	gypsumRecyclingEOL

Polyethylene vapour barrier membrane, 0.15 mm, 0.14 kg/m2 (One Click LCA)	1	m2	0.15	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)	0.004	m3		560.0	-1.0	17.9	woodIncinerationE-OL
Thermoplastic polyolefin (TPO) membrane roofing, 0.06in	1	m2	1	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
XPS insulation panels, L=0.035 W/mK, R=2.85 m2K/W, 100 mm, 3.8 kg/m2, 38 kg/m3, compressive strength 500 kPa, 40% recycled polystyrene, CO2 blowing agent, Lambda=0.035 W/(m.K) (One Click LCA)	1	m2	150	350	-1.0	4	plasticBasedMaterial-IncinerationEOL
Ready-mix concrete, Québec industry average, 30 Mpa Concrete with air entrainment (F- 1) GU (Association béton Québec (ABQ))	1	m2	203.2	200	-1.0	4	concrete300kgCe-mentToAggrega-teEOL
Reinforcement steel (rebar), generic, 60% recycled content, A615 (One Click LCA)	48	kg		580	-1.0	4.85	steelRecyclingEOL
W5 - Alum below	1	m2					
Alkyd emulsion-based paint, 1.2 kg/l, pigment volume concentration 15.8 v%, solvent weight 1 m% (One Click LCA)	0.000	m3		800.0	10.0	10	inertMaterialLandfill-ingEOL
Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft3)	1	m2	16	200.0	-1.0	12.5	gypsumRecycling-EOL
Polyethylene vapour barrier membrane, 0.15 mm, 0.14 kg/m2 (One Click LCA)	1	m2	0.15	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)	0.004	m3		560.0	-1.0	17.9	woodIncinerationE-OL
Thermoplastic polyolefin (TPO) membrane roofing, 0.06in	1	m2	1	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
XPS insulation panels, L=0.035 W/mK, R=2.85 m2K/W, 100 mm, 3.8 kg/m2, 38 kg/m3, compressive strength 500 kPa, 40% recycled polystyrene, CO2 blowing agent, Lambda=0.035 W/(m.K) (One Click LCA)	1	m2	150	350	-1.0	4	plasticBasedMaterial-IncinerationEOL
Roll formed aluminum cladding, 2.77 kg/m2 (Metal Construction Association)	1	m2		580	-1.0	7.5	aluminumRecyclin-gEOL
Ready-mix concrete, Québec industry average, 30 Mpa Concrete with air entrainment (F- 1) GU (Association béton Québec (ABQ))	1	m2	203.2	200	-1.0	4	concrete300kgCe-mentToAggrega-teEOL
Reinforcement steel (rebar), generic, 60% recycled content, A615 (One Click LCA)	48	kg		580	-1.0	4.85	steelRecyclingEOL
W4 - Brick above	1	m2					
Alkyd emulsion-based paint, 1.2 kg/l, pigment volume concentration 15.8 v%, solvent weight 1 m% (One Click LCA)	0.000	m3		800.0	10.0	10	inertMaterialLandfill-ingEOL
Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft3)	1	m2	16	200.0	-1.0	12.5	gypsumRecycling-EOL
Polyethylene vapour barrier membrane, 0.15 mm, 0.14 kg/m2 (One Click LCA)	1	m2	0.15	350.0	30.0	10	plasticBasedMaterial-IncinerationEOL
Fiberglass insulation in batts, unfaced, R-5.68 (Rsi=1 m2K/W), 1.381 kg/m2, Unfaced Fiberglass, Kraft Faced Fiberglass, Panel Deck FSK-25, FSK-25, ComfortTherm®, Cavity-SHIELD™ (Johns Manville)	4.48	kg		200.0	-1.0	8	inertMaterialLandfill-ingEOL

Wooden stud framing for drywall/gypsum plasterboard per sq. ft of wall area (incl. air gaps per m3), 2x6 in, 16 in spacing, headers incl. for 8 ft wall height (American Wood Council, Canadian Wood Council)	1	m2		560.0	-1.0	17.9	woodIncinerationEOL
Softwood plywood, 477.33 kg/m3 (Canadian Wood Council)	0.019	m3	127	560.0	-1.0	16.7	woodIncinerationEOL
Stone wool (mineral wool) insulation, unfaced, L = 0.0325 W/mK, R = 1 m2K/W, 32.5mm, 5.04 kg/m2, 155 kg/m3, (Range: 113-200kg/m3), 22% slag content, high pressure suitable (One Click LCA)	1	m2	50	200.0	-1.0	8	inertMaterialLandfillingEOL
Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)	0.004	m3		560.0	-1.0	17.9	woodIncinerationEOL
Air and water barrier system, mechanically fastened, 0.0451 lbs/ft2, 0.22 kg/m2, Tyvek (DuPont)	1	m2		350	30.0	10	plasticBasedMaterialIncinerationEOL
Clay brick, 2120 kg/m3 (Acme Brick Company, Belden Brick Company, Bowerston Shale Company, Brampton Brick, Inc., Endicott Clay Products Co., General Shale, Inc., Glen-Gery Corporation, Hebron Brick Company, Lee Brick & Tile Company, Meridian Brick LLC, Meridian Brick Canada Ltd., Pine Hall Brick, Inc., Statesville Brick Company)	0.092	m3		200	-1.0	5	inertsToAggregateEOL

	Intensity	Original Area	Total Original	Proposed Area	Total Proposed		Carbon Intensity	Floor Area	Total Non-basement carbon	Total Project carbon Original	Total Project Carbon Proposed	Percent Dif
Concrete	570	21.3	12141	18.2	10374		250	180.5	45125	72836	62804.8	14%
Foundation	17	64	1088	64	1088		500	180.5	90250	117961	107929.8	9%
W1-alum above	53	0	0	10.2	540.6							
W3-brick below	181	68.4	12380.4	0	0							
W4-Brick above	83	0	0	68.4	5677.2							
W5-alum below	206	10.2	2101.2	0	0							
Total			27710.6		17679.8		1.567	times more carbon than above grade				

Barrier #6: Exposed Mass Timber Floor Assemblies

The LCA for Barrier #6: Exposed Mass Timber was conducted using the OneClick LCA tool. Material EPDs were selected based on industry experience and analysis of current construction standards. The hypothetical comparison takes place in British Columbia, and as such, the concrete EPDs represent British Columbia industry averages and transportation distances are adjusted automatically. In order to capture the variation of material sourcing, assemblies A-C are duplicated with a high emission and low emission scenario each. A significant portion of emissions from all assemblies are the result of gypsum board. Full LCA available upon request to author.

MATERIAL	QUANTITY	QTY_TYPE	THICKNESS_MM	TRANSPORTDISTANCETRACI_KM	SERVICE LIFE	WASTESHAREINUSEPHASE	EOLPROCESSID
E	1	m2					
Ready-mix concrete, 35MPa Industry Average Benchmark (CRMCA)	0.15	m3	203.2	200.0	-1.0	4	concrete300kgCementToAggregateEOL
Reinforcement steel (rebar), generic, 80% recycled content, A615	12	kg		580	-1.0	4.85	steelRecyclingEOL
D	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCementToAggregateEOL
Hollow core concrete slabs, generic, C40/50 (5800/7300 PSI), 20% recycled binders in cement (400 kg/m3 / 24.97 lbs/ft3), incl. reinforcement	0.2	m3	265	200.0	-1.0	0	reinforcedConcreteToAggregateEOL
B - High	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCementToAggregateEOL
Cross laminated timber (CLT), 481 kg/m3, 12% (± 3%) moisture content (One Click LCA)	0.18	m3		560.0	-1.0	16.7	woodIncinerationEOL
Glass-mat gypsum boards, fire and moisture resistant, 15.9 mm, 13.59 kg/m2, 855 kg/m3, Type X (American Gypsum Company LLC, CertainTeed Gypsum, Inc., CGC INC., Continental Building, Products Operating Company, LLC, Georgia–Pacific Gypsum LLC, National Gypsum Company, PABCO Gypsum, LLC, and United States Gypsum Company)	1	m2	24.5	200.0	40.0	12.5	gypsumRecyclingEOL
B - Low	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCementToAggregateEOL
CLT produced in British Columbia, 464.7 kg/m3 (Forestry Innovation Investment)	0.18	m3		560.0	-1.0	16.7	woodIncinerationEOL
Fire resistant gypsum boards for wall and ceiling, 12.7 mm (1/2 in), 9.8 kg/m2, 2438-3658 x 1219 mm, Type X, 1/2 in. Sheetrock ® Brand Firecode ® C and Mold Tough ® Panels Firecode ® C (USG)	0.025	m3	12.7	200.0	40.0	12.5	gypsumRecyclingEOL

C - High	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCement-ToAggregateEOL
Cross laminated timber (CLT), 481 kg/m3, 12% (± 3%) moisture content (One Click LCA)	0.18	m3		560.0	-1.0	16.7	woodIncinerationEOL
C - Low	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCement-ToAggregateEOL
CLT produced in British Columbia, 464.7 kg/m3 (Forestry Innovation Investment)	0.18	m3		560.0	-1.0	16.7	woodIncinerationEOL
A - High	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCement-ToAggregateEOL
Cross laminated timber (CLT), 481 kg/m3, 12% (± 3%) moisture content (One Click LCA)	0.14	m3		560.0	-1.0	16.7	woodIncinerationEOL
Glass-mat gypsum boards, fire and moisture resistant, 15.9 mm, 13.59 kg/m2, 855 kg/m3, Type X (American Gypsum Company LLC, CertainTeed Gypsum, Inc., CGC INC., Continental Building, Products Operating Company, LLC, Georgia–Pacific Gypsum LLC, National Gypsum Company, PABCO Gypsum, LLC, and United States Gypsum Company)	1	m2	24.5	200.0	40.0	12.5	gypsumRecyclingEOL
A - Low	1	m2					
Ready-mix concrete, British Columbia industry average, Baseline 15 MPa Concrete without air entrainment (N) GU 30 SCM (Concrete BC)	0.05	m3	203.2	200.0	-1.0	4	concrete200kgCement-ToAggregateEOL
Fire resistant gypsum boards for wall and ceiling, 12.7 mm (1/2 in), 9.8 kg/m2, 2438-3658 x 1219 mm, Type X, 1/2 in. Sheetrock ® Brand Firecode ® C and Mold Tough ® Panels Firecode ® C (USG)	2	m2	12.7	200.0	40.0	12.5	gypsumRecyclingEOL
CLT produced in British Columbia, 464.7 kg/m3 (Forestry Innovation Investment)	0.14	m3		560.0	-1.0	16.7	woodIncinerationEOL

	10% Exposed	40%
Total	400	
Blow -Encap	50	
B high - Encap	67	
Clow - Exposed	38	
% exposed	10%	40%
Total Floor B low	48.8	45.2
Total Floor B high	64.1	55.4
Total floor % B low	12.2%	11.3%
Total floor % B high	16.0%	14%
		0.9%
		4.7%

	25%	100%
Total	400	
Blow -Encap	50	
B high - Encap	67	
Clow - Exposed	38	
% exposed	25%	100%
Total Floor B low	47	38
Total Floor B high	59.75	38
Total floor % B low	11.8%	9.5%
Total floor % B high	14.9%	10%
		2.3%
		5.4%