education sciences

Article

Structural Timber Design in Curricula of Canadian Universities: Current Status and Future Needs

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Abstract: Due to the efficiency, sustainability, and advances in firefighting technologies, the allowable height for wood buildings was increased from 4 to 6 storeys in 2015 and will be further increased to 12 storeys in the 2020 edition of the National Building Code of Canada, as a result of the advent and application of mass timber products. To match the development in the industry and the increasing need in the market for highly skilled timber engineers, structural timber design curricula at the university level must evolve to train the next generation of practitioners. At most Canadian universities, structural timber design courses are mainly provided in civil engineering departments. In this study, 31 accredited civil engineering programs in Canada were reviewed for structural wood design content at undergraduate and graduate levels based on two surveys conducted in 2018 and 2020. In the 2018 survey, the percentage of structural timber design content was estimated and compared with other engineering materials (e.g., steel, concrete, and masonry), and a similar survey was repeated in 2020 to determine if any significant changes had occurred. In early 2021, two complementary questionnaires were sent to the instructors of timber-related courses across the country to collect quantitative information, including enrollment statistics, percentage dedicated to timber design in combined material courses, and potential topics deemed critical to support the design of modern timber structures. Based on the responses provided, and also on the availability of resources and the research ongoing, the content for five advanced-level courses is proposed to address the needs of the timber design community. The findings presented in this paper will assist the timber industry, government agencies, and educational institutions in effecting potential changes to university curricula to educate the next generation of timber design professionals who will possess the necessary skills and knowledge to meet the challenges in designing modern mass timber structures.

Keywords: timber design education and curriculum; sustainability; timber engineering; survey; decision matrix; advanced timber design courses

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1. Introduction

According to Environment and Climate Change Canada, the building sector ranked third for greenhouse gas (GHG) emissions after the oil and gas industry and the transportation sector, as shown in Figure 1 [1]. Urbanization in North American cities has been steadily increasing, and it is estimated that by 2050, there will be an additional 2.3 billion people moving to cities [2]. This urbanization trend has led to an increase in mid- and high-rise multi-family buildings that are predominantly constructed from steel and concrete. While these conventional construction materials possess phenomenal mechanical characteristics, their large environmental footprints are a source of concern.

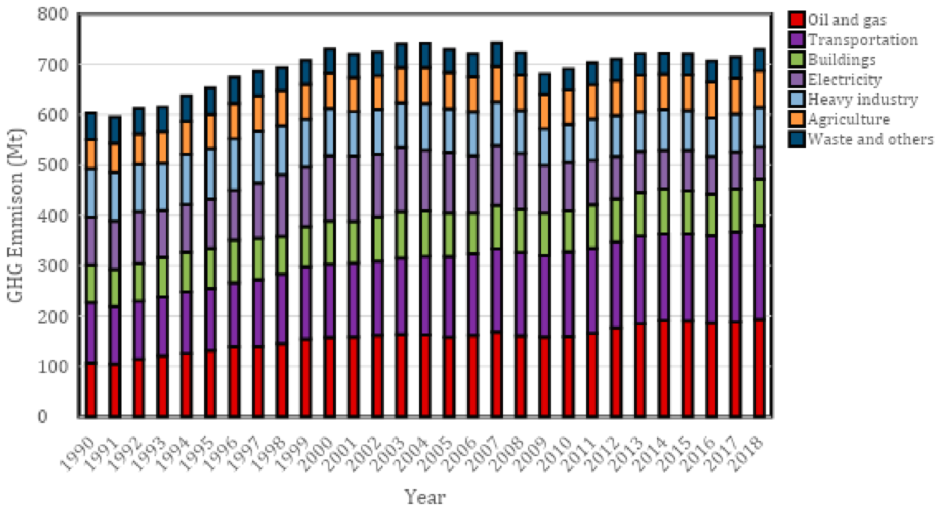


Figure 1. GHG emissions by Canadian economic sectors from 1990 to 2018 ([1]; redrawn and reprinted with permission).

Wood is one of the most widely accepted structural materials in North America for low-rise and mid-rise buildings using traditional light wood frame construction. In Canada, the storey limit for timber buildings was four when it was first imposed in 1941 [3] and did not change until after the 2010 revision of the National Building Code of Canada [4]. This limitation was mainly due to concerns regarding fire safety in buildings, as firefighting capabilities were inadequate at the time. A historical breakthrough for timber buildings occurred in 2009 when the Province of British Columbia approved an amendment [5] to the 2006 British Columbia Building Code [6] and increased the building height limit to six storeys. Although the revision of the storey limit in BCBC only applied to residential light wood platform frame construction, it raised the interest level of researchers, designers, and builders in timber buildings beyond the traditional boundaries.

With the advent of mass timber products (loosely defined as products that have a smallest dimension of at least 89 mm), such as cross-laminated timber (CLT), glue-laminated timber (GLT), and nail-laminated timber (NLT), a renaissance occurred in the application of wood as a primary structural material. While charring has been proven as an inherent material-specific attribute of mass timber products against fire [7,8], the enhanced understanding of fire spread in buildings achieved by fire-resistance tests, combined with innovative firefighting technologies, has provided building authorities with more confidence to push the boundaries of mid-rise mass timber buildings [9–11]. From a structural standpoint, a key design concern related to seismic performance was addressed by the availability of innovative and high-capacity ductile connections [12–16]. From a sustainable design perspective, mass timber mid-rise and high-rise buildings can act as a global carbon sink [17], as carbon is stored over the life of the building (Figure 2). The publication of the first edition of the CLT Handbook [18], the tall wood buildings guide [19], and CLT structural design provisions in the Canadian timber design standard [20] have all contributed to the increased use of mass timber in building construction in Canada. In view of the interest in mass timber mid-rise and high-rise buildings, the National Building Code of Canada (NBCC) approved an increase in storey limit from four to six storeys for wood construction in 2015 [21]. The storey limit for wood buildings is expected to be further increased to 12 storeys in the 2020 edition of NBCC. In addition to multi-family residential buildings and high-rise structures, there is an increased interest in using timber in industrial, commercial, and institutional typologies and infrastructure, such as bridges [22].

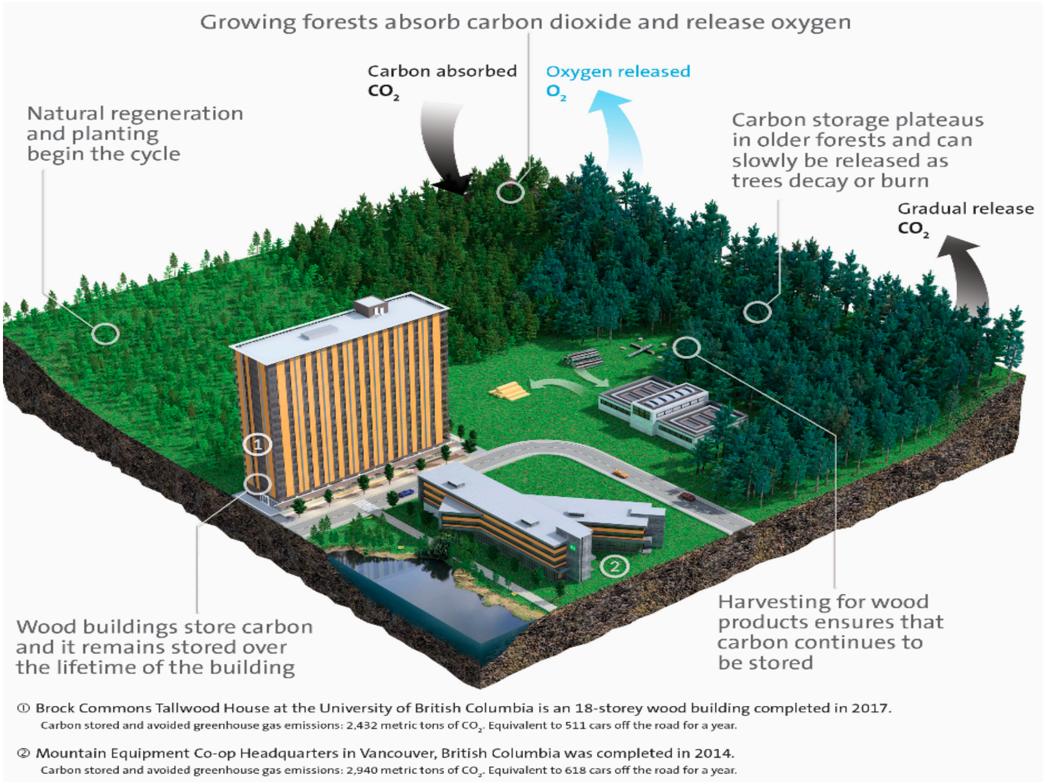


Figure 2. Tackling climate change with mass timber buildings (reprinted with permission, courtesy of Naturally Wood [23]).

To meet the demands of skilled professionals in designing more complex, taller, and larger timber structures, university curricula must evolve to provide appropriately trained graduates to the design community. At Canadian universities, structural timber design courses are mainly offered in civil engineering departments, with a few exceptions (e.g., the Faculty of Forestry at the University of British Columbia offering courses in advanced wood physics and mechanics and the School of Architecture at the University of Waterloo offering timber design courses). In this study, 31 accredited undergraduate civil engineering programs and graduate courses related to structural timber design were reviewed to determine the current structural timber design curricula in Canada. All undergraduate structural design courses were identified in two surveys conducted in 2018 and 2020. For each identified course, the percentage of timber content was estimated and compared with the content of other engineering materials (i.e., steel, concrete, masonry, and aluminum).

Two complementary questionnaires were also sent to the instructors of timber-related courses: one for undergraduate design courses that have partial timber content (called combined or multi-material courses in this study) and the other for full timber undergraduate and graduate design courses. In the former, information on enrollment and the percentage of the course dedicated to timber design was requested for the 2020–2021 school year. The collected information provided an indication of the status of the structural timber design content at Canadian universities. In the latter, instructors were asked about enrollment, main topics covered in their courses, and potential topics that, in their opinion, should be taught in the future. Educational gaps were identified based on the responses received and a previous study on research priorities, leading to the proposition of five advanced level courses. The proposed courses were designed not only to be comprehensive and contain topics that are frequently encountered by designers but also to include less common topics (e.g., design for blast loading or curved beams). Therefore, these courses can be used as a part of a program aiming to meet immediate and medium-term needs of the North American structural timber design community.

2. Research Methodology

There have been several studies and surveys [24–28] in the U.S. aimed at evaluating the amount of timber education in the country, highlighting deficiencies and providing solutions. However, the number of similar studies in a Canadian context was limited [29], and there were no survey results specific to Canadian universities in recent years. Past survey results in the U.S. revealed that timber design courses are not offered to the same extent as steel and concrete design courses. In 2016, the U.S. National Council of Structural Engineers Associations (NCSEA) performed an extensive structural engineering curriculum survey in which accredited civil engineering and other related programs were surveyed regarding the reasons why timber design courses were not offered [27]. Figure 3 provides a summary of these results.

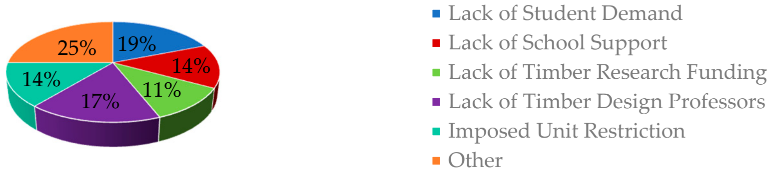


Figure 3. Reasons for not offering timber design courses similar to steel and concrete courses in the U.S. [27].

Lack of research funding for timber, lack of professors specializing in timber research, and lack of school support were cited as the main reasons for the shortage of timber design courses, accounting for 42% of the responses. As schools typically support topics with high funding opportunities, it seems evident that timber education content offered by an institution is largely linked to whether its professors are engaged in research in timber. Moreover, research needs often offer an insight into future competency needs in university graduates. With these connections between research and education in mind, it would be beneficial to study the results from a recent survey conducted by two of the authors to identify mass timber research needs and priorities in Canada [30]. In this study, the questions were not directly related to educational needs, but the results were considered when the curricula for advanced courses were developed.

As part of the education roadmap initiative led by the Canadian Wood Council (CWC), two education surveys were conducted to collect information on timber design education at undergraduate and graduate levels in Canada. The first survey was performed in 2018 and focused on courses in accredited civil engineering programs at Canadian universities based on information posted online. All structural design courses (core and elective) in undergraduate programs were reviewed and categorized geographically. Graduate level timber engineering courses were also reviewed.

A more comprehensive survey was conducted in 2020 to collect enrollment statistics and investigate the progress in offering timber design courses, considering the rising demand and accomplished research in this area. The results of the two surveys were analysed together. In addition, questionnaires were included in the 2020 survey to collect some statistics on timber course content and enrollment. For undergraduate design courses that considered a mixture of structural materials, the percentage of the course dedicated to timber was determined (less than 25%, between 25% and 50%, between 50% and 75%, or above 75%). Additionally, information on the number of students enrolled in these classes (less than 10, between 10 and 30, between 30 and 60, or more than 60) was obtained. For the timber only courses, in addition to the enrollment number, instructors were asked to provide a list of topics covered in the course as well as any potential topics not currently included but considered important to teach in the future. Based on the list of potential topics collected, a decision matrix was developed, and conclusions were drawn with respect to subjects that should be added to university curricula and their priorities to enhance the structural timber design capabilities of university graduates. The research methodology is summarized in Figure 4.

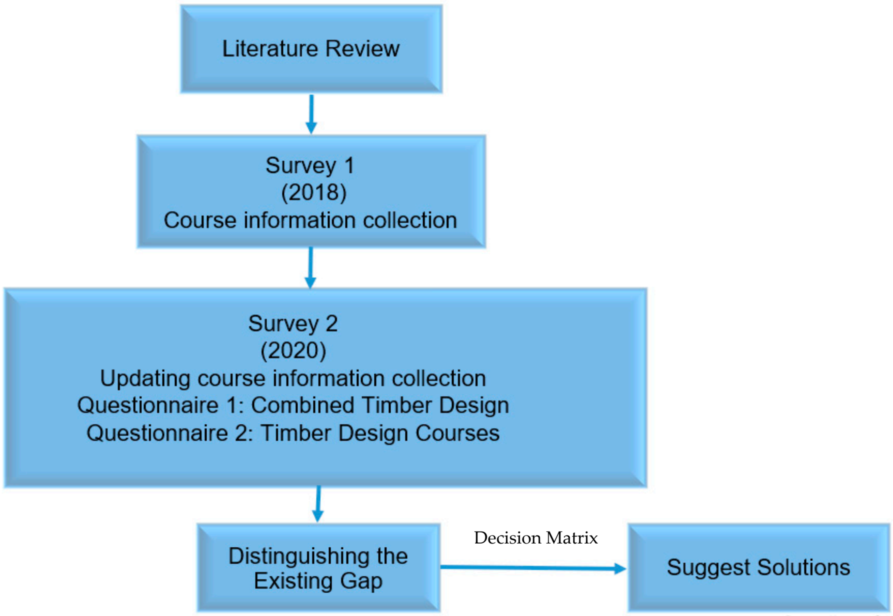


Figure 4. Summary of the methodology and procedure.

3. Literature Review to Identify Technical Challenges in Mass Timber Applications

To determine the needs in timber education, a literature review was conducted on the current research inventory and perceived technical gaps on mass timber in Europe, the U.S., and Canada. Espinoza et al. [31] investigated key research areas for the progression and growth of CLT in Europe, based on Dillman's Tailored Design Method [32]. The study surveyed European experts in timber engineering regarding research areas that are important for the advancement of CLT as a dominant mass timber product in the market. A total of 51 responses were received out of 93 emails sent, resulting in a response rate of 53.8%. The survey showed that over 90% of respondents indicated that 'Structural Performance' and 'Connections' were the most critical research need. 'Moisture performance', 'Market/Customer Research', and 'Acoustic Performance' were highlighted as medium research priorities.

In a consequent study, Espinoza et al. [33] conducted a web-based survey in North America. It listed ten potential research topics of importance and asked the participants to rank them in five categories, from 'very high priority' to 'very low priority'. A total of 47 responses were received out of 105 emails sent, resulting in a 46.1% response rate. Results of the research needs are summarized in Figure 5. 'Seismic Performance', 'Connectors and Fasteners', and 'Fire Performance' were the most prioritized research areas.

In 2018, USDA Forest Products Laboratory held the Mass Timber Research Workshop to identify future research needs in the U.S. [34]. The result was 180 research topics divided into seven categories. The top category was 'Designing to Resist Structural Resiliency', followed by 'Durability and Building Physics' and 'Fire Performance' and 'System Design and Construction', as shown in Figure 6. Forestry Innovation Investment conducted another survey of U.S. research projects. The distribution of the 60 research projects recognized in 2018 is shown in Figure 7 [35]. The top category was 'Seismic, Wind and Structural Performance', and 'Fire Performance' was ranked fourth after 'Cost, Market and Adoption' and 'Durability'.

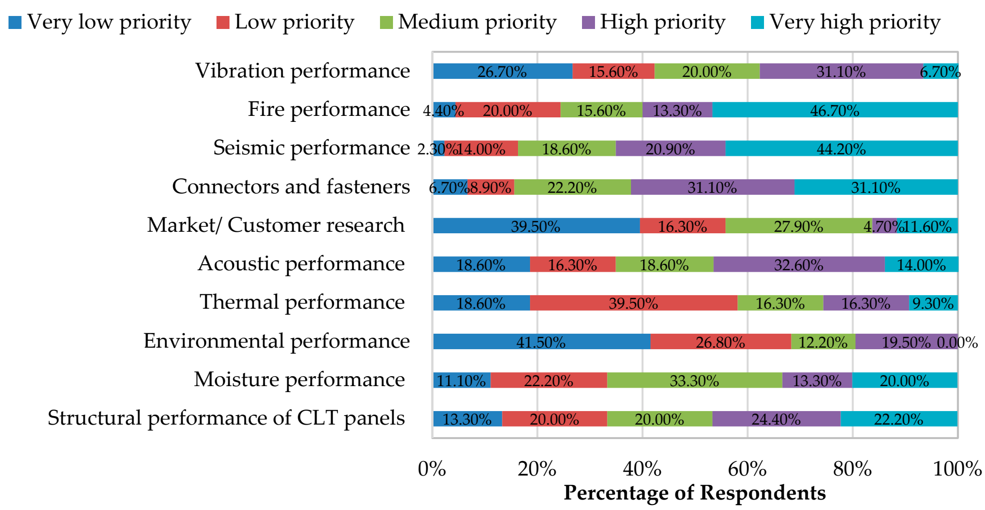


Figure 5. Ranking of research needs in North America [33].

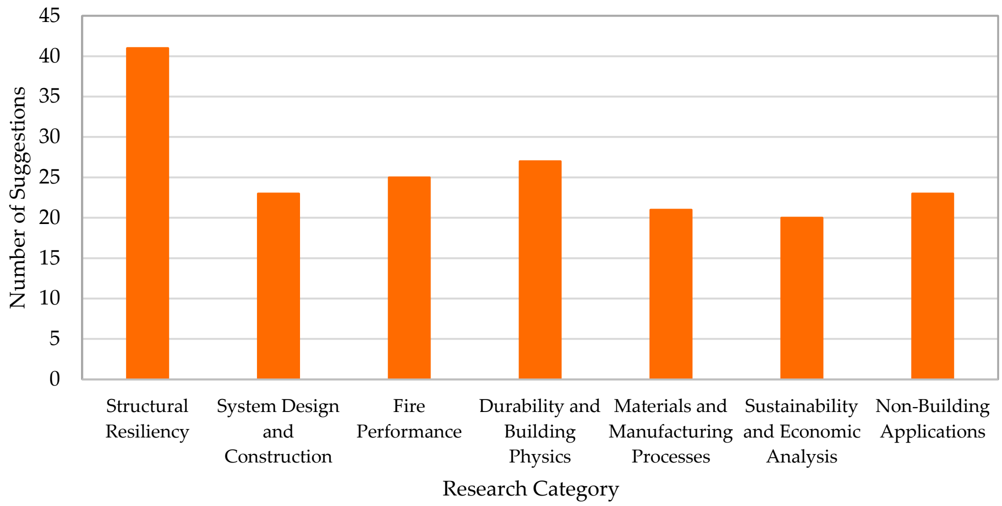


Figure 6. Number of research needs identified in the 2nd Mass Timber Research Workshop [34].

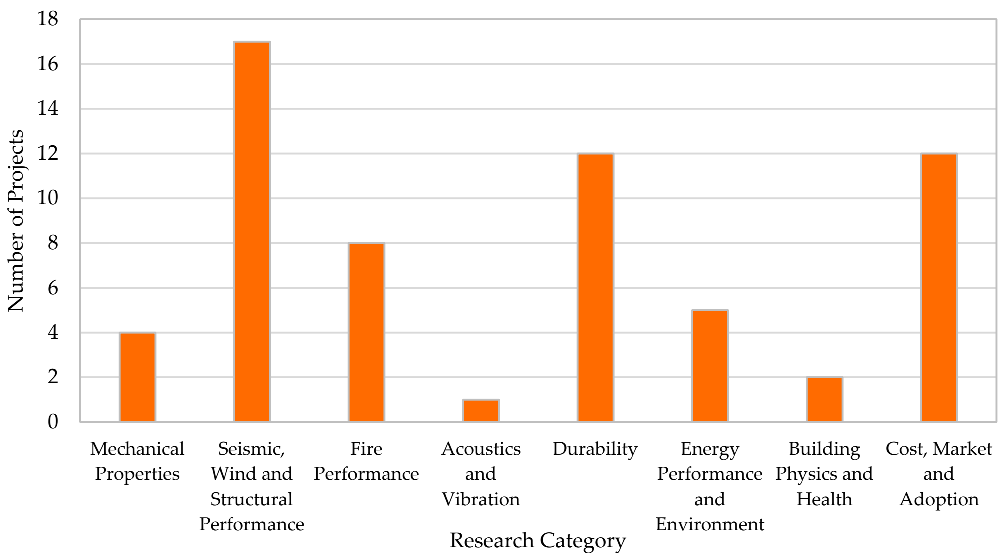


Figure 7. Number of mass timber research projects in progress in the U.S. (as of 2018; [35]).

Advanced Research in Timber Systems (ARTS) at the University of Alberta performed an extensive survey in 2019 to characterize the research landscape in Canada related to mass timber structures. Information on recently completed and in-progress research was obtained and analysed to identify research priorities and technical challenges in Canada. According to the survey results from structural consultants in the country, the competency of new graduates is the main challenge faced in the industry. A total of 63% of experienced practising structural engineers highlighted the limited knowledge of graduated design students in wood capabilities for complex form creation, especially when combined with concrete or steel ('treat timber the same way they would use for steel'). Half of the correspondents emphasized the necessity of specialized structural courses at the university level in mass timber construction to fill the gap in knowledge.

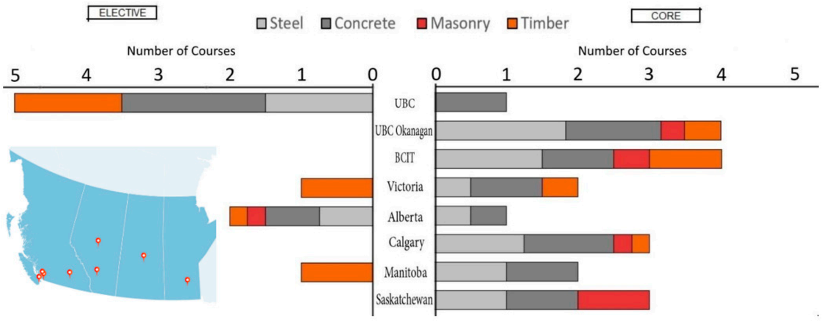
Based on the survey results, a summary of key research themes and topics that require immediate attention from the research community (so-called Immediate Research Projects) and medium-term projects (mentioned by the respondents but not as frequently as the first group) is presented in Table 1 [30]. It should be noted that fire performance was not listed as an important research topic in Europe [31], contrary to American [33] and Canadian survey results [30]. This difference in priority may be due to the lack of prescriptive height limitation for timber buildings, as some European countries (e.g., United Kingdom and Switzerland) adopt performance-based regulations [30]. Many research topics suggested in [30] are similar to the ones proposed by instructors across the country in terms of education (discussed in Section 5), which proves the strong correlation between research and education at the post-secondary level.

Table 1. Proposed immediate and medium-term research projects [30].

Topic	Immediate Research Projects	Medium-Term Research Projects
Connections and Fasteners	• High performance connections • Design provisions of fasteners (e.g., self-tapping screws)	• Glued-mechanical connections (e.g., glued-in rods)
Fire Performance	• Fire design of connections • Fire design of exposed mass timber • Fire during construction	• Performance-based fire design methodology (e.g., removal of combustible vs. non-combustible construction type)
Seismic and Wind Performance	• Energy dissipative connection systems • Diaphragm action • Seismic force modification factors for mass timber balloon construction • Braced timber frame system	• Prediction of natural period and lateral drift • Design method for structural resiliency
Acoustic and Vibration of Floor Systems	• Cost-effective acoustic details • Vibration design	• Effective solutions to enhance floor performance
Construction Method	• Application of advanced construction engineering tools (e.g., building information modelling) • Costing tools for builders	• Integrated approach to design, production, and construction of mass timber buildings • Modularization solutions
Sustainability	• Framework to quantify benefits of mass timber that encompass forestry, construction, infrastructure, and related sectors	• Quantification of the socio-economic and environmental benefits of mass timber

4. Survey Results and Discussion

Figure 8 presents the findings from the 2018 survey based on geographical territories: British Columbia and Prairies, Ontario, and Quebec and Atlantic Provinces (separated into English and French courses). The results of the 2020 survey are reported in Figure 9. Each structural material is colour-coded, and the results for core and elective courses are presented separately. Each unit represents one course, and materials are assumed to be covered equally when the course content includes more than one material. The accumulative percentage of steel, concrete, timber, masonry, and aluminum covered in undergraduate programs for the 2018 and 2020 surveys is shown in Figure 10. Figure 11 shows the distribution of graduate-level timber courses in the 2018 and 2020 surveys.



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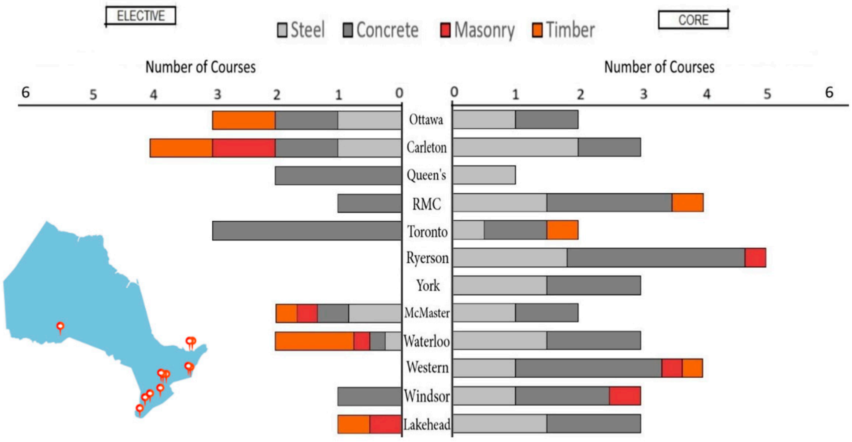

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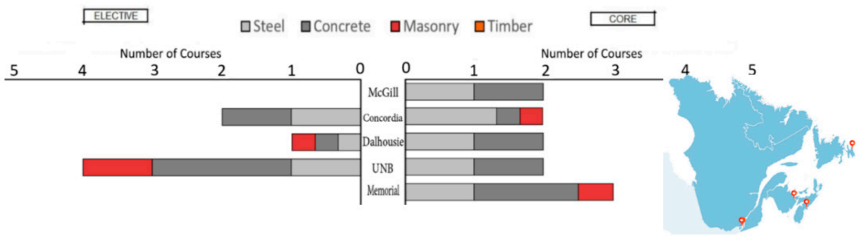

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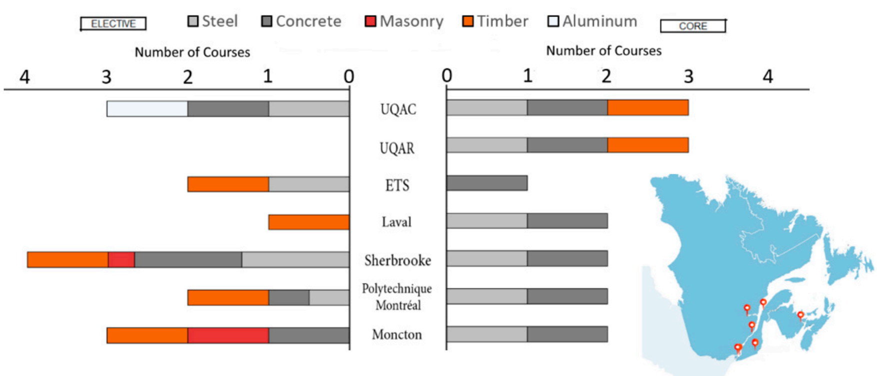


(**d**)

Figure 8. Undergraduate design courses based on the 2018 survey in (**a**) British Columbia and Prairies, (**b**) Ontario, (**c**) Quebec and Atlantic (English courses), and (**d**) Quebec and Atlantic (French courses).

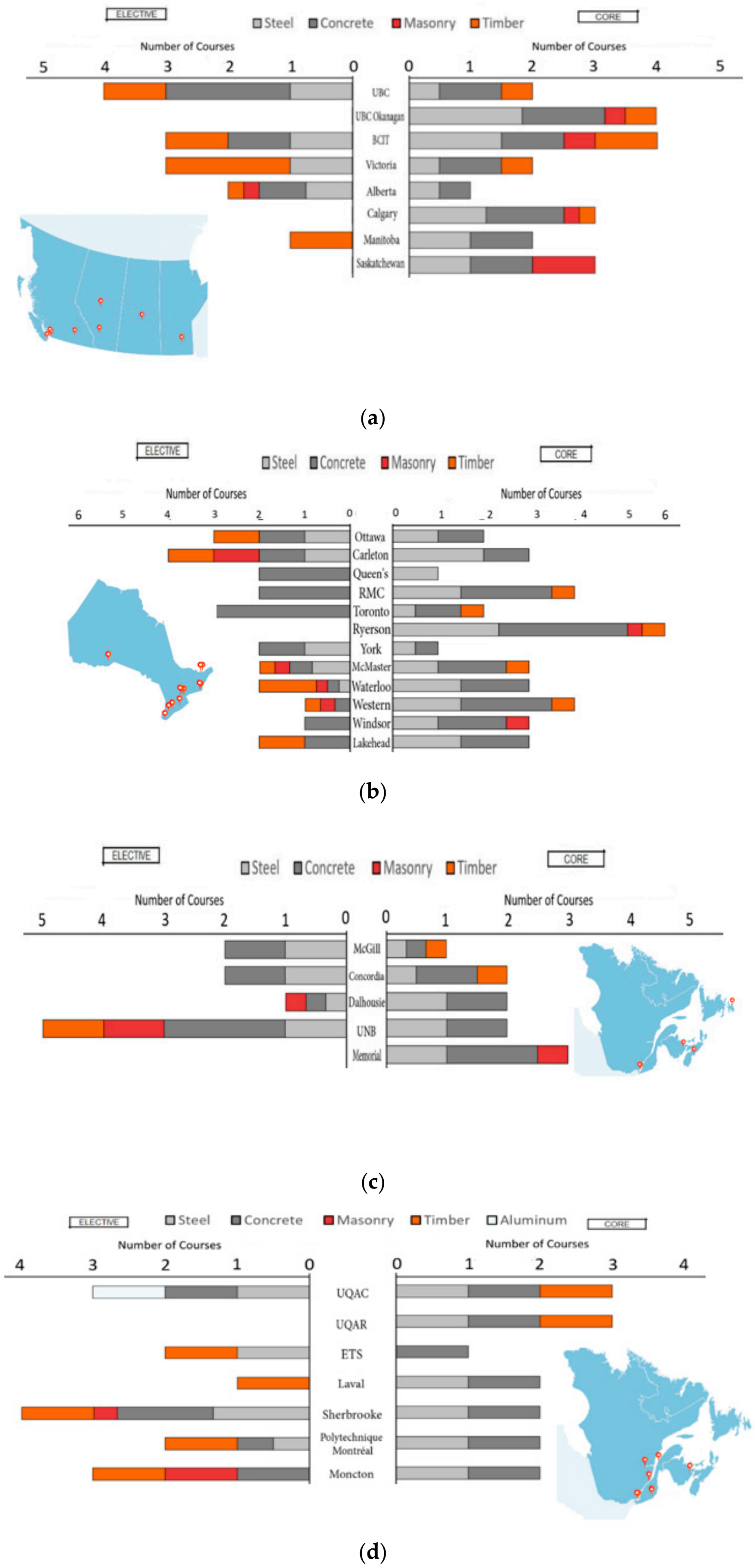
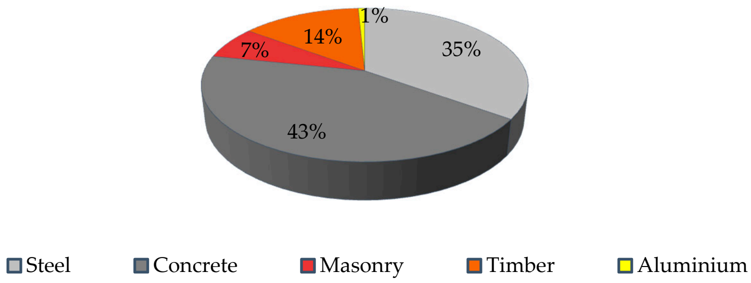


Figure 9. Undergraduate design courses based on the 2020 survey in (**a**) British Columbia and Prairies, (**b**) Ontario, (**c**) Quebec and Atlantic (English courses), and (**d**) Quebec and Atlantic (French courses).



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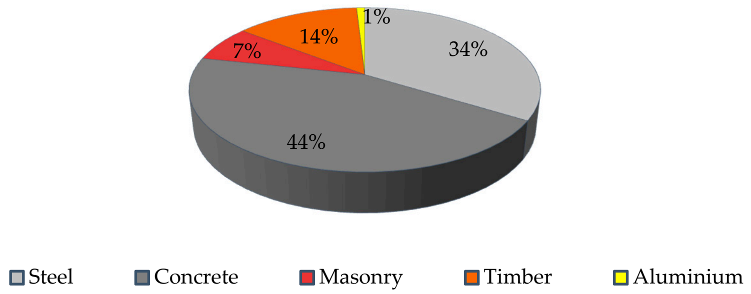


(**b**)

Figure 10. Percentage of steel, concrete, timber, masonry, and aluminum covered in undergraduate programs from the (**a**) 2018 and (**b**) 2020 surveys.

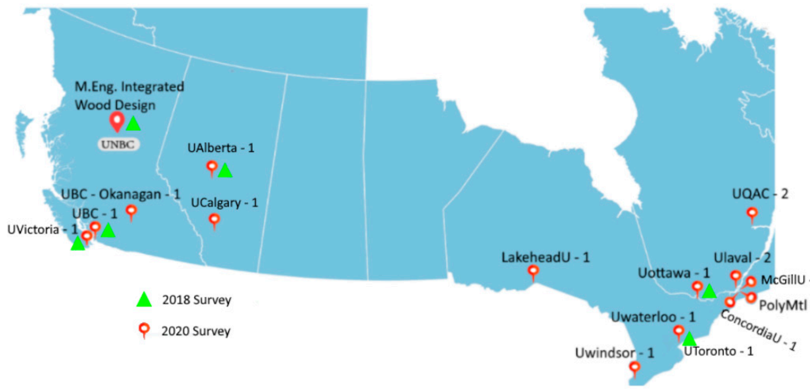


Figure 11. Number of graduate timber design courses based on the 2018 and 2020 surveys in Canada.

Results of the two surveys reveal that there are a few universities with limited or no timber education at the undergraduate level. Based on Figures 8 and 9, the number of timber undergraduate courses in British Columbia have generally increased for both core and elective courses (two new courses), while there was no change at the universities in the Prairies. There is no timber component in Manitoba, and the undergraduate timber education in Alberta and Saskatchewan is very limited (less than one full course). Some minor improvements can be observed in core courses offered in Quebec and Atlantic English-speaking programs, while no change was observed in French programs in that region. However, the number of timber undergraduate courses at French-speaking universities is considered significant compared with other parts of the country (seven full timber courses in seven universities), most likely due to local government support that promotes sustainable timber material in the construction industry. Despite a few minor increases in timber engineering at Ontario universities, there were no substantial changes observed. In general, the number of structural timber components appears to be increasing at the same rate as steel (eight new multi-material courses containing steel and timber, while six of those also contain concrete) within the two-year period; however, the timber portion remains significantly lower than that of steel and concrete, as shown in Figure 10. Based on the 2020 survey results, at least one core or one elective combined timber course is offered at 14 and 17 universities (45% and 55% of all universities considered), respectively.

As the demand for timber design courses at the undergraduate level increases, departments are encouraged to offer more of these courses. While there are limited opportunities to add new core courses to existing programs, appending wood design elements to design courses (e.g., in capstone design projects) or adding elective timber courses is more practical, particularly the ones that are offered to senior undergraduate and graduate studies. Requests to add these new elements or elective courses are often initiated by individual faculty members. Incentives to faculty members to offer timber design courses, such as teaching resources, research support, timber laboratory facilities, and timber design software, will facilitate this process. These incentives can be provided by universities or associations interested in promoting wood education e.g., CWC.

Despite minor improvements at the undergraduate level, Figure 11 reveals a significant growth in the number of graduate timber courses. According to the 2018 survey, there were 5 graduate timber courses, while 16 timber design courses were identified in the 2020 survey. At the graduate level, there is a correlation between wood research expertise and available wood design courses. As the number of professors engaged in timber engineering research grows, the number of graduate timber courses offered across the country should also increase. However, the current curriculum of all available courses is not accessible online or reported elsewhere. As a result, questionnaires were necessary to develop a better understanding of the current state of timber education across the country.

5. Questionnaire Results and Discussions: Educational Needs and Proposed Remedies

As part of the 2020 survey, questionnaires were sent to the instructors of 33 undergraduate and 17 graduate timber-related courses as well as one timber engineering program. The participation percentages of the survey are summarized in Table 2, where participation was more than 80% in all categories. Out of 33 undergraduate design courses, 20 were combined design courses (i.e., more than one material), 11 were exclusively timber courses, and 2 were cross undergraduate–graduate courses. In the case of cross undergraduate–graduate courses, both undergraduate and graduate students attend the same class but have distinct course requirements.

Table 2. Summary of participation in different categories.

Course Level	Number of Requests Sent	Number of Responses Received	Participation (%)
Undergraduate combined design course	20	18	90
Undergraduate timber course	11	9	82
Cross undergraduate–graduate course	2	2	100
Graduate timber course	17	15	88
Graduate timber program	1	1	100

Figure 12 shows the percentage of timber content in undergraduate multi-material design courses, which is less than 50% for the majority of these courses. Figure 13 shows the undergraduate and graduate enrollment levels (typically more than 60 for the combined multi-material courses), while enrollment varies between 10 and 60 for the timber courses at both undergraduate and graduate levels. Results of the questionnaires, shown in Figures 12 and 13, reveal that the percentage of timber content in the undergraduate design courses is limited; most of the content of combined design courses is dedicated to other engineering materials (mainly steel and concrete).

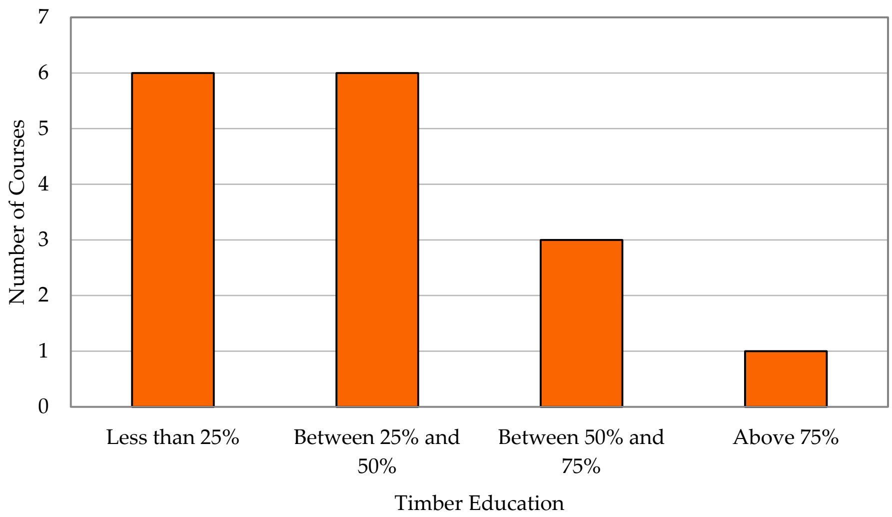
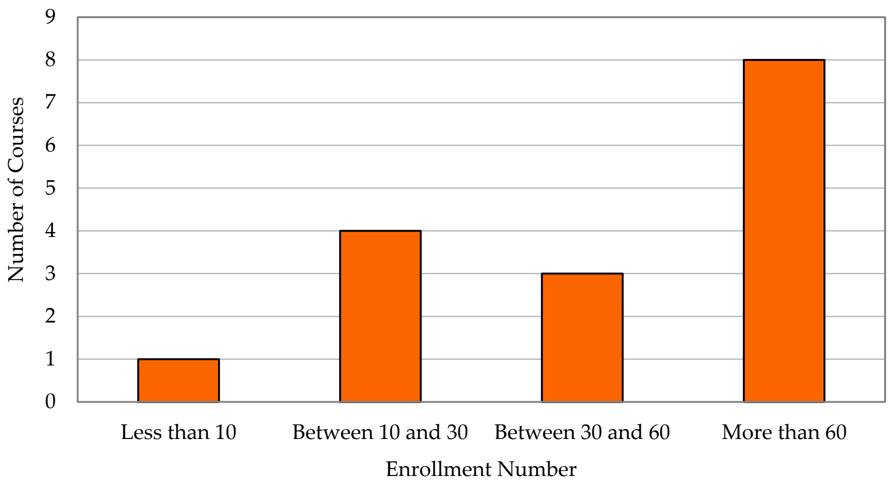


Figure 12. Percentage of timber content in undergraduate combined design courses.



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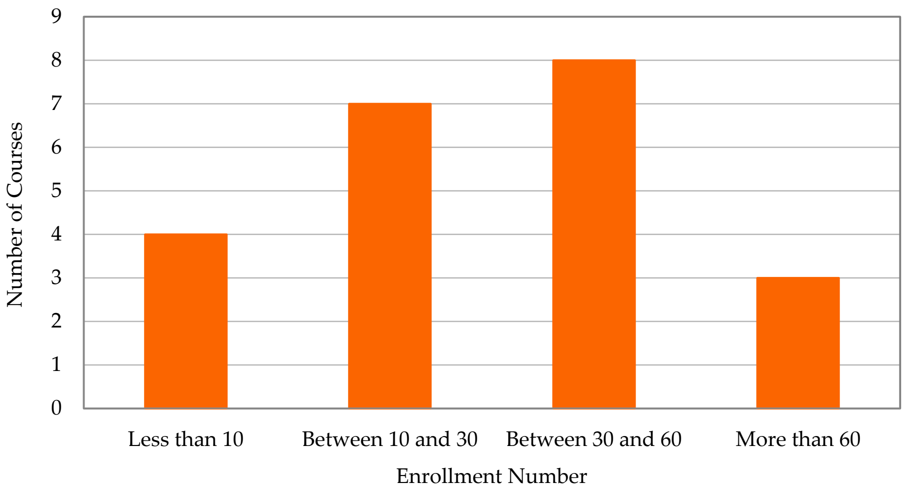

(**b**)

Figure 13. Enrollment number in (**a**) combined (mostly undergraduate courses) and (**b**) timber design courses (undergraduate and graduate courses).

The estimated number of students exposed to timber in such combined courses (with an approximate average of 33% timber content) ranges from 610 to 1110, with an average of 860, per academic year. Similarly, the estimated number of students exposed to all timber design courses, at both undergraduate and graduate levels, is between 490 and 1030, with a median of 760 in Fall 2020 and Winter 2021 semesters. The estimated number of students interested in taking timber courses is significant, and departments are encouraged to offer timber design courses as the demand increases.

Table 3 summarizes the responses of instructors on topics currently covered in courses and potential topics that should be taught in the future. The former is separated into two categories: general topics that are mostly identical among different courses and specific topics that are unique to one or two courses. Most of the current curriculum of timber at the undergraduate level focuses on the design of light wood frames and their pertinent connections, with a few exceptions that discuss mass timber structures in a limited scope. Two courses cover specific topics of designing wood formworks for concrete structures, as well as examining the properties of wood, including material failure and phase equilibrium. Although most of the instructors stated time limitations as the main constraint in covering more material during a semester, a few expressed interest in including mass timber design, particularly CLT or fire safety design.

Table 3. Summary of current topics for timber design courses in Canada.

Level	Current Topics	
	General	**Specific**
Undergraduate Timber Courses	• Physical and mechanical properties of wood • Wood strength and modification factors and grading • Design of wood components (sawn lumber and glulam) in bearing, bending, compression, tension, and combined loading • Light wood frame diaphragm and shear walls • Design of screwed, nailed, and bolted connections	• Concrete formworks • Wood physics: orthogonality, material failure, and phase equilibrium
Graduate Timber Courses	• Topics covered in the undergraduate level (depending on the program) • Derivation of design values and design methods: ultimate and serviceability limit states • Wood durability and preservation • Design mass timber structures (mostly CLT) • Connection design of mass timber components	• Finishing (preparation of wood surface) • Bracing systems • Design of wood elements subjected to fire • FEM of mass timber structures • CWC Design Office software

At the graduate level, the curriculum varies significantly based on the presence of an undergraduate timber design course. In lieu of undergraduate courses on basic wood design in the program, the graduate course covers such topics in addition to more in-depth material (e.g., limit state design philosophy of wood products, design of mass timber products subjected to various loading scenarios, and designing CLT diaphragms and shear walls). Several specific topics have also been suggested by instructors, such as finishing, bracing systems, fire design, and finite element modelling (FEM) of timber members.

The responses regarding potential topics that should be taught in the future were divided into undergraduate and graduate courses, as shown in Figure 14. CLT design is the main topic that instructors wish to include at the undergraduate level, given its adoption into CSA O86 in 2016. Seismic, fire, vibration, and composite design as well as long span structures (e.g., timber bridges) are other potential topics suggested by instructors across the country. At the graduate level, connection design ranked first, followed by mid-rise and high-rise structures as well as modular construction. In addition to these design topics, finite element analysis (FEA) of timber structures and life cycle assessments (LCA) were also indicated by one instructor.

The topics that instructors considered to be significant in future curricula included seismic analysis and design of mass timber structures, design of timber floors for human-induced vibration, long span, composite and hybrid systems design, connections in mass timber structures, mid-rise and high-rise building design, modular mass timber construction, and LCA. These new topics are all imperative but should be prioritized based on immediate industry needs and may require specialized instructors to cover the niche material. Guest lecturers, consultants, visiting professors, and mass timber suppliers are recommended to fill the existing gap between academia and industry. However, the most effective method is to hire new faculty with diverse industrial backgrounds to teach such topics while integrating their teaching endeavours with research. In the next sections, these topics are further analyzed via a decision matrix tool and then presented as five new graduate level courses as a solution to fill the existing gaps.

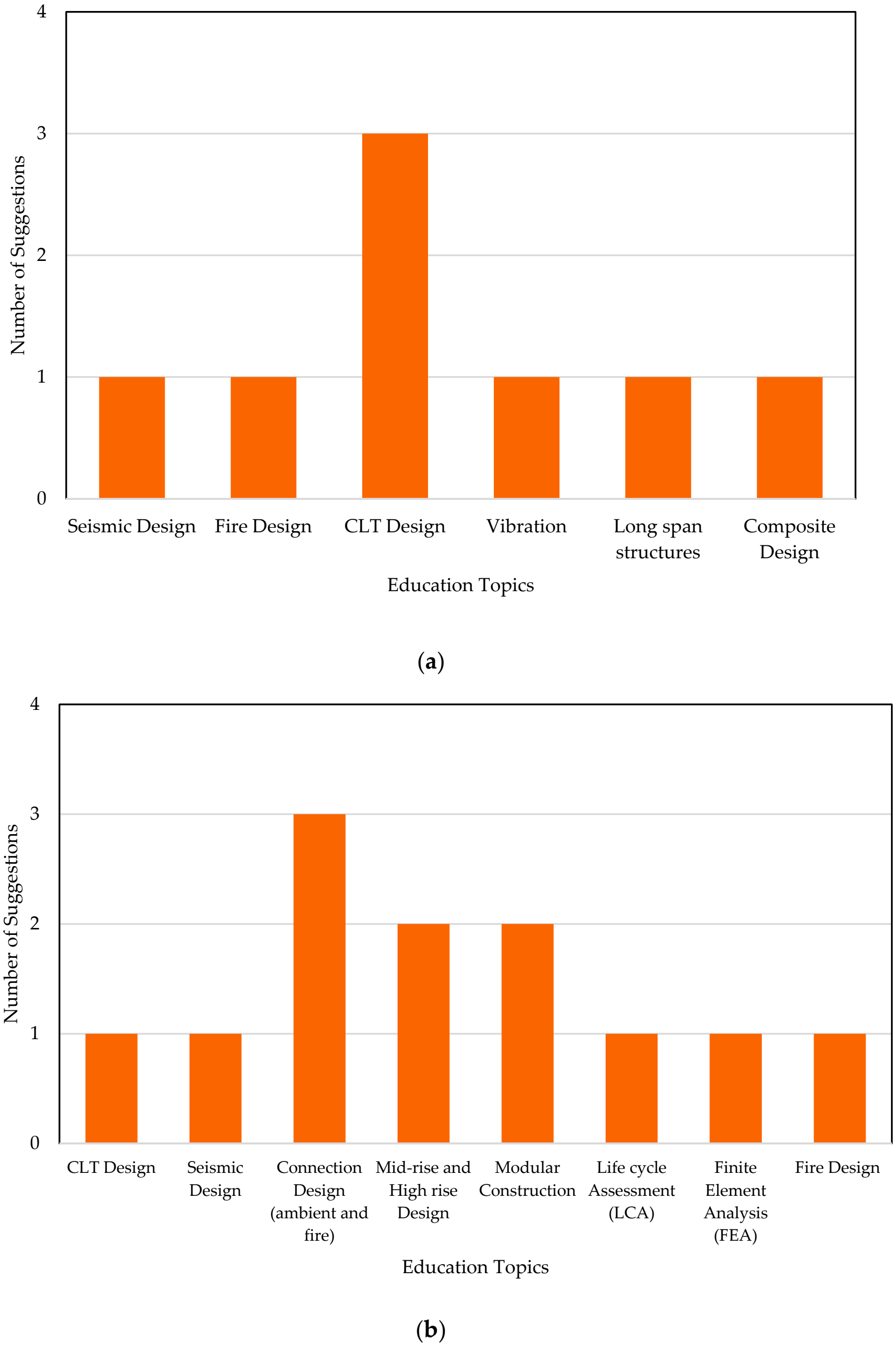

Figure 14. Potential topics suggested by instructors for (**a**) undergraduate and (**b**) graduate courses (8 and 12 respondents for suggestions, respectively).

6. Developed a Decision Matrix Tool

Based on the results of previous surveys that identified mass timber research needs and priorities, mainly the most recent one performed in Canada [30], and the results of the surveys and questionnaires discussed as a part of this study, a decision matrix table analytic tool was developed to prioritize the required topics to be covered at the graduate level. The table is organized into rows of topics and columns of criteria. Based on the survey results and the authors' previous research results, fifteen topics and three criteria were selected, as shown in Table 4. Each criterion is scored on a scale of 0–10; the higher the number, the more suitable the criterion in supporting the topic. In order to apply the significance of each criterion, different weights were considered. Since this study relied on the survey results, mainly the instructors' feedback, the highest weight is allocated to their suggestions. In addition, availability of relevant resources (resources that can be used to produce course content effectively) is deemed more important than the compatibility to the research needs. However, similar to any other decision matrix tools, other weights can be employed to serve objectives of a study, considering different circumstances. More information regarding the assumptions is brought in the footnote of Table 4.

Table 4. Input for decision matrix.

No.	Topic	Criterion 1 [1]	Criterion 2 [2]	Criterion 3 [3]
		Weight		
		3	**2**	**1**
1	VLRS Design	6	10	1
2	VLRS Connections	3	10	10
3	Vibration	1	5	10
4	LLRS Design	8	10	10
5	LLRS Connections	3	5	10
6	Rehabilitation/Retrofit	0	1	1
7	Composite Members	1	10	5
8	Hybrid Systems	0	1	10
9	Large Span Systems	1	1	1
10	Fire Design	5	10	10
11	FEA	1	5	1
12	Structural Integrity	0	1	5
13	Manufacturing/Construction	0	5	10
14	Modularization	1	1	5
15	Sustainability	1	1	10

[1] Instructors' suggestions: Based on the survey results (Figure 14). [2] Availability of relevant resources: Based on the research performed on the teaching reference available—10 points: There are more than 10 relevant resources available to teach the course effectively; 5 points: There are 5 to 10 relevant references available teach the course effectively; 1 point: The amount of relevant resources is limited (fewer than 5 resources). [3] Compatibility with research needs: Based on the authors' research to identify the research gaps (Table 1)—10 points: The topic is mentioned as immediate research need; 5 points: The topic is mentioned as medium-term research need; 1 point: The topic is not mentioned.

By multiplying the assumed weights for the criteria, the priority of each topic can be calculated, as shown in Table 5. Additionally, by considering the themes of the topics and categorizing them into the courses, the priority of each course can be calculated as well. As can be seen, courses with the main theme of VLRS and LLRS design obtained scores of 101 and 86, respectively, constituting the highest priority courses, followed by the course on protective design of mass timber buildings (total score of 66).

Table 5. Output for decision matrix.

Course No.	No.	Topic	Criterion 1 [1]	Criterion 2 [2]	Criterion 3 [3]	Scores	
			Weight			Topics	Courses
			3	2	1		
1	1	VLRS Design	18	20	1	39	101
	2	VLRS Connections	9	20	10	39	
	3	Vibration	3	10	10	23	
2	4	LLRS Design	24	20	10	54	86
	5	LLRS Connections	9	10	10	29	
	6	Rehabilitation/retrofit	0	2	1	3	
3	7	Composite members	3	20	5	28	46
	8	Hybrid Systems	0	2	10	12	
	9	Large Span Systems	3	2	1	6	
4	10	Fire Design	15	20	10	45	66
	11	FEA	3	10	1	14	
	12	Structural Integrity	0	2	5	7	
5	13	Manufacturing/Construction	0	10	10	20	45
	14	Modularization	3	2	5	10	
	15	Sustainability	3	2	10	15	

[1–3]: See Table 4 footnotes.

7. Proposed Advanced Graduate Level Courses

According to the literature survey discussed earlier in the Section 3, and also the survey results discussed in the Sections 4 and 5, the educational gap was identified in the higher education level as a need for more specialized mass timber design courses. Based on the results of the decision matrix discussed in the previous section (Section 6), the curricula for five advanced graduate level courses were developed. It should be noted, since the proposed courses are designed to cover specialized advanced topics, previous knowledge of timber design obtained by a general timber undergraduate or graduate course, as a prerequisite, is strongly suggested. The Bloom's Taxonomy [36] (comprises six major categories of remember, understand, apply, analyze, evaluate, and create) was employed to ensure that the outcomes of the proposed courses were aligned with new research trends in sustainable timber-built environments. For example, by having a thorough design example as the last component of each course, it is assured that students can develop the capability to produce new or original design (ability to 'create' as the pinnacle of Bloom's Taxonomy), while exercising the principles of sustainability. A summary of course descriptions, proposed topics, and intended outcomes for these courses is discussed below.

7.1. Design of Mass Timber Components and Buildings

This course was designed to familiarize students with the fundamentals of mass timber design, mainly focused on the design of different components of the vertical load resisting system (VLRS) of the mass timber structures, particularly CLT buildings due to their superior mechanical properties and market popularity. However, other mass timber products such glulam, NLT, GLT can be discussed as required. A few advanced topics compatible with the content of the course are included in the proposed outline:

i. Design requirements
   1. Design value development and stress grades
   2. Material properties and modification factors (e.g., load duration factor, treatment factor, volume effects, moisture content)

ii. Member design
   1. Bending and shear design of CLT panels, including analytical models
   2. Design of walls and columns under concentric and eccentric loadings
   3. Lintel or beam design

iii. Advanced topics
   1. Reinforcement of holes and notches
   2. Design for lateral torsional buckling
   3. Tapered and curved elements

iv. Vibration performance and design
v. Connection design
    1. Common fasteners (e.g., screws, nails, bolts, and rivets)
    2. Connection design using innovative fasteners (e.g., self-tapping screws and glued-in rod)
    3. Various connection design (e.g., in-plane connections, corner connections, and wall to floor/roof/foundation connections)
vi. Full design of VLRS of a CLT building (design examples)

7.2. Lateral Design of Mass Timber Systems

As mass timber building geometry increases in height and becomes more complex, the need for lateral load resisting systems (LLRS) designed for major seismic and high wind effects has increased. In addition, there is a significant demand for connections as part of LLRS. Proper stiff and ductile connection design is of primary importance for achieving the intended design criteria for a given application. The proposed outline focuses on two main LLRS (i.e., CLT shear walls and timber-braced frames) to fill in the educational gaps in this area:

i. Performance-based seismic and wind design methods as well as capacity-based design vs. conventional lateral design methods
ii. Dynamic material properties and modification factors (e.g., load duration factor, shrinkage, creep, fatigue, and strain rate effects)
iii. Ductility definition and different classes in connection design
iv. Innovative and proprietary connections
v. CLT shear walls and pertinent connections
    1. Platform construction
    2. Balloon construction
vi. Timber-braced frames
vii. Diaphragm systems and connections of vertical elements to horizontal elements
viii. Design for high wind and tornados
ix. Retrofit and rehabilitation techniques
x. Full lateral design of a mass timber building (design example)

7.3. Protective Design of Mass Timber Structures

Mass timber mid-rise and high-rise timber buildings are unique types of structures with their own characteristic behaviours. They are occupied by many people, and their damage and loss of functionality in different scenarios (e.g., fire or blast, or collapse) will lead to catastrophic consequences in the community. As a result, it is necessary for designers, engineers, and practitioners involved in the design process to be familiar with the available methodology and state-of-the-art practices in this area. Although mass timber buildings are recognized as having superior performance in resisting fire, there are special conditions required by various jurisdictions to ensure their safety, particularly in high-rise construction. In addition, it is vital for practitioners designing such buildings to be familiar with methodologies and philosophies intended to provide structural integrity or increase structural robustness, thereby making structures resistant to disproportionate collapse. Knowledge of advanced modelling methods, particularly FEA, is a prerequisite to the evaluation of timber members and structures against such extreme loadings. As a result, the third course addresses the educational needs in these areas.

i. FEA of mass timber assemblies and systems
    1. Material properties and input for ambient and elevated temperature
    2. Modelling and analysis methods
    3. Model verification and interpretation of results
ii. Fire performance and design

1. Fire characteristics of wood
2. Fire-resisting tests of mass timber products
3. Construction types and requirements
4. Design for fire safety
5. Fire safety during construction

iii. Design to mitigate progressive collapse

1. Introduction to structural integrity, robustness, and progressive collapse
2. Review of progressive collapse guidelines and related clauses of selected building codes
3. Design methods (i.e., direct and indirect)
4. Alternate load paths in mass timber systems subjected to vertical element removal scenario
5. Design considerations to mitigate progressive collapse

iv. Design for blast loading

1. Blast load characteristics and calculations
2. Review of blast guidelines and related clauses of building codes
3. Performance of mass timber panels subject to blast loading

v. Protective design of a mass timber building for fire, progressive collapse, and blast (design example)

7.4. Mass Timber Hybrid, Composite, and Long-Span Systems

Although mass timber products have unique engineering characteristics, there are some inherent weaknesses, and consequently, there are opportunities to enhance their behaviour, both as a structural element and as a system, combined with other structural material (mainly steel and concrete). The focus of the fourth proposed course is on mass timber hybrid structural systems as well as timber–concrete composite floors. The course is completed with a module on mass timber bridges.

i. Pros and cons of using timber with other engineering materials
ii. Timber–steel and timber–concrete hybrid systems
iii. Timber–concrete composite floors

1. Partial composite action beam theory
2. Shear connector systems
3. Design for ultimate limit states: shear, bending, and connectors
4. Design for serviceability limit states: short- and long-term deflection and vibration

iv. Timber bridges

1. Introduction to timber bridges: systems, technology, and construction
2. Design of timber bridges according to available bridge codes
3. Timber bridge design examples

v. Design of a hybrid mass timber building with composite floors (design example)
vi. Design of a medium- to long-span mass timber bridge (design example)

7.5. Construction of Sustainable Mass Timber Systems

While the first four courses are purely structural, the fifth proposed course is designed to focus on different aspects of mass timber construction. Building information modelling, the main trend in the construction industry, as well as prefabrication and modularization, are other subjects that will be discussed, although research in these areas is ongoing. The last component of the course is the sustainability of mass timber construction, with a focus on LCA as one of the most widely accepted mechanisms for investigating the environmental impacts of different phases of a building's life cycle.

i. Mid-rise and high-rise mass timber construction

1. Why mass timber? Project examples and best applications

2. Types and configurations based on building codes
3. Fire rating, structural, shrinkage, acoustic requirements, and applicable detailing
4. Construction efficiency: prefabrication and smart digital design
5. Transportation, lifting, and handling

ii. Building information modelling (BIM)

1. Available tools
2. Project planning and implementation strategies
3. Quality, risk, and business management

iii. Modular construction

iv. Sustainability

1. Definitions
2. Life cycle assessment (LCA), whole building LCA (WHLCA), and available tools
3. Strategies to reduce life cycle impacts
4. Framework to quantify environmental benefits of mass timber products
5. Quantification of environmental and socio-economic benefits of mass timber buildings

v. LCA of a sample mass timber building (design example)

There are other specialized topics that may be included in the curriculum of such advanced courses, depending on the expertise of the instructor and interests of the potential audience (e.g., bracing systems for timber members). In addition to the *CLT Handbook* [8] and *Wood Design Manual* [37], the upcoming *Advanced Wood Engineering Manual* by CWC is a valuable source for educators for such advanced topics in timber areas. It is noted that an additional course on building enclosure design and hydrothermal analysis of mass timber buildings was deemed as an appropriate supplement to the five proposed courses to develop a comprehensive graduate-level program in mass timber engineering. However, the development of such a course is out of the scope of this pedagogical research endeavour.

8. Summary and Conclusions

In the past century, steel, concrete, and masonry have been the primary structural materials used in the construction industry. As a result, the vast majority of educational offerings in engineering design have been dedicated to these materials. While wood is still trailing far behind concrete and steel as the structural material of choice for high-rise and complex structures, mass timber construction in North America, particularly in Canada, is increasing, mainly due to construction efficiency and for sustainability reasons.

In this study, the status of timber design curricula from 31 accredited civil engineering programs of Canadian universities, at both undergraduate and graduate levels, was investigated. Based on two surveys conducted in 2018 and 2020, the percentage of timber design at the undergraduate level was compared with other engineering materials (e.g., steel, concrete, masonry, and aluminum). Two complementary questionnaires were also sent to the instructors of timber-related courses across Canada to determine enrollment statistics, percentage of the course dedicated to timber design, main topics covered in these courses, and potential topics that should be taught in the future.

Considering the increasing market demand for niche sustainable solutions, it is estimated that the number of students interested in taking timber courses will increase in the next few years. Departments are encouraged to offer mass timber design courses as the demand increases by benefitting from instructors with diverse design experience. Based on the responses provided by timber instructors across Canada, an educational gap was identified in higher education that shows a need for more specialized mass timber design courses. The curricula for five advanced level courses were presented to address the immediate and medium-term needs of the mass timber industry, which can be used to develop a comprehensive graduate-level program in mass timber engineering. This study reports the status of timber engineering education across Canada and aims to assist timber design educators in Canada and other jurisdictions on topics that must be included in a timber engineering curriculum at advanced levels that will eventually push the boundaries of mass timber research, education, and design even further.

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Abbreviations

CLT	Cross-laminated timber
CWC	Canadian Wood Council
FEM	Finite element modelling
FEA	Finite element analysis
GHG	Greenhouse gas
GLT	Glue-laminated timber
LCA	Life cycle analysis
LLRS	Lateral load resisting systems
NLT	Nail-laminated timber
VLRS	Vertical load resisting systems

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