Exploring the Regional-scale Potential of the Use of Wood Products in Non-residential Buildings: A Building Permits-based Quantitative Approach

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In the construction sector, wood products are gaining interest. Methods are necessary to quantify material use and evaluate their potential effects. When quantifying the building material consumption, many studies are limited to residential buildings due to the lack of data for non-residential buildings. This research aimed at investigating a methodology to account for non-residential building material consumption. A method to estimate the volume of wood products in the structures of the new non-residential buildings was presented. Then, projections of the estimation were suggested according to three scenarios (minimum, average, and maximum). Sensitivity analyses highlighted the parameters that present the greatest contribution to the scenarios. The relative importance of the estimation to the total harvesting of all wood markets was also assessed. Despite the high uncertainty in wood consumption for non-residential building structures, the estimation had a small weight on the total harvesting of the Quebec province. The results showed how and when the resource availability could be constrained depending on the assumptions. This method can serve for life cycle inventory for an environmental assessment or wood flow analysis, but more research on the material composition of the non-residential building archetypes is necessary.

Keywords: Non-residential buildings; Structure; Wood products; Wood building; Building stock

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INTRODUCTION

Interest in wood has been increasing in the construction sector. Indeed, Gosselin *et al.* (2017) recently documented increased motivation for the use of wood in construction (including the decrease of barriers and their change over time) (Gosselin *et al.* 2017). This is mainly explained by the improvement of wood products in recent years with respect to environmental and technical properties (Hurmekoski *et al.* 2015), as well as fire performance (Laguarda-Mallo and Espinoza 2015), including different building code implementation, and expertise (Geskin Conseil 2008; Espinoza *et al.* 2015; Robichaud 2017; Ratnasingam *et al.* 2018). The availability of materials in the market is also seen as a main driver for the use of wood in the US region (Laguarda-Mallo and Espinoza 2016). The cost also may be as much of a motivation (Levée *et al.* 2018) as it is a barrier. In Quebec, main factors that could contribute to the use of wood are technical design guides, ongoing training, structural costs, and ease of its estimation (Robichaud 2017).

In Quebec, the Wood Charter provides a roadmap to increase the use of wood in non-residential (NR) construction (MFFP 2017). In single-family houses, where around 1 to 2 floors are the norm, light-frame wood construction represents approximately 90% of this sector. For NR buildings, some surveys estimate the market share (28% of buildings, of 4 stories and less, have wood structure (Robichaud 2017)), but the amount of wood that is used is still unknown. With the Wood Charter, the government and wood companies work to increase its consumption in NR buildings. In addition to technological advances and the synergy established between industrial and institutional players, examples of high and medium height wooden buildings and the continuous public communication (*e.g.*, the use of wood magazines) can play a role in the acceptance of high-rise wood buildings. Indeed, the above examples demonstrate the feasibility of wood-based structures for high-rise buildings in North America (*e.g.*, in British Columbia with the Brock Common and the Wood Innovation and Design Centre (WIDC), the T3 office building in Minneapolis, and in Quebec, the Origine, *etc.*). However, these examples may represent a technical reality at the scale of the building itself but not a large-scale feasibility for an entire building cohort. This emerging market, supported by private and institutional investments and by governmental initiatives, may imply changes in the supply chain of raw materials and in the management of wood products. Therefore, it is necessary to understand wood product flows at the economic sector scale as an important step for policy measurement. For environmental assessments or other anthropological activity assessments, an inventory of wood product flows in the NR building stock is necessary. However, methods are needed to quantify wood consumption.

RESEARCH BACKGROUND AND OBJECTIVE

The following subsections present different aspects of research focusing on the temporal quantification of wood material in the building sector.

Building Material Consumption

When quantifying the building material consumption, many studies are limited to residential buildings due to the lack of data for non-residential buildings (Augiseau and Barles 2017; Göswein *et al.* 2017). The literature reports that the building stock evolution does not depend on the same parameters that drive the material consumption of the residential sector. Indeed, the non-residential building stock depends on the industrial activity or the concentration of headquarters in specific cities (Göswein *et al.* 2017). Even if the methods may vary related to assumptions and available data, an overall trend exists in the methodology. The main methodological approach for studying current flows and stocks is a bottom-up approach involving the following three steps:

1) Estimating characteristic material compositions indicators (MCIs - mainly in kg/m^2) regarding the various building archetypes in the cohort under assessment;

2) Estimating the physical size of the building stock in terms of one unit measure (such as total floor space – m^2);

3) Multiplying the two first points to obtain the inventory of materials (Bergsdal *et al.* 2007; Shi *et al.* 2012; Huang *et al.* 2013; Ortlepp *et al.* 2016). The literature itself clearly mentions a lack of research for MCIs for non-residential buildings (Ortlepp *et al.* 2016).

For studies focusing on the NR buildings, (Nepal *et al.* 2016; Ortlepp *et al.* 2016; Huang *et al.* 2017), the method is the same as the common one for residential buildings (*i.e.*, total surface area of buildings multiplied by the material intensity (kg/m^2) per building type (Huang *et al.* 2013)). When data is not already available, authors use other proxies. Lichtensteiger and Baccini did their own investigations to estimate the material content of NR buildings (Lichtensteiger and Baccini 2008). Another approach to creating information on the material composition of NR building stock type considers the use of geographical information systems (GIS). Schebek *et al.* have combined existing spatial data and data gained from real case studies investigations to help represent different typologies. The GIS was carried out based on the combination of those data (Schebek *et al.* 2017). Tanikawa and Hashimoto (2009) also estimated the material stock using urban-scale GIS data. In addition to physical parameters, economical parameters give other insights. To separate the portion of wood products for NR buildings among the total construction demand, Nepal *et al.* (2015) introduced the yearly shift in demand and the price elasticity of the total and the NR demand. Ortlepp *et al.* (2016) estimated the area-wide gross volume in terms of regional floor space. They broke it down into building types with a monetary value. With economic data such as the gross stock of fixed assets, their procedure followed three main steps: a) the use of Germany's non-domestic buildings value estimation (in monetary terms) with national accounting data (VGR); b) the transformation of monetary values into physical quantities (m^2 floor space), with correlation factors; and c) the allocation of the total floor to each building. Another estimation with monetary values considers the building permit with the share of wood structure and the price of lumber (Geskin Conseil 2008). The suggested formula implies an overestimation of wood in building structures because it considers the price of lumber instead of the price of the installed wood structure. This current paper highlighted that MCIs of NR buildings are far less known. However, in NR buildings, the main challenge for the MCI is that the buildings cover a large disparate range of functionalities, sizes, and safety requirements.

Drivers Identification and Projection

When building material consumption is estimated, projecting this consumption is another challenge. It requires identifying the “drivers” of the consumption. These drivers are determinant parameters influencing the consumption of the sector. The main driver in developed countries is the population (Müller *et al.* 2014; Nepal *et al.* 2016; Huang *et al.* 2017; Kayo *et al.* 2018). With this parameter, the gross domestic product (GDP) or other macroeconomic indicators of the sector (*e.g.*, the area per capita in m^2/P) are also determinant parameters illustrating human activities. They act as driving forces in long-term change studies (Huang *et al.* 2017). Equation 1 describes the commonly used equation to study the impact of human activities with the parameters,

$$I = P * A * T \tag{1}$$

where I is the indicator of Impact, P is the population, A is the affluence (such as GDP/P or m^2/P, *etc.*). Those two parameters (P and A) are commonly available in yearly statistics and help to set the scale of the studied sector and to drive its evolution. The last parameter (T) stands for the technology, such as the material intensity (such as the MCI).

Thus, projecting the consumption can imply projecting those three parameters. Two approaches exist for the projection of the flows depending on the parameters and its historical availability. The approaches are either retrospective or prospective (with exploratory scenarios) (Buyle 2018). Retrospective presents a low level of uncertainty because it assumes that the historical trends are representative for future scenarios (especially for a relatively short time horizon) (Weidema 2003). Prospective mostly refers to expected future developments (Buyle 2018).

Upstream of the Building Sector

Material flow analysis (MFA) is a tool to quantify the flows and stocks of materials in arbitrarily complex systems. It is widely applied to investigate resource use, material losses, and waste management (Laner and Rechberger 2016). According to Parobek *et al.* (2014), wood flow analysis generally tackles resource use but seldom products, because official data neither cover individual distribution channels in different sectors nor products purchased by individual consumers. This reinforces that wood flow analysis requires more empirical research and data collection (Parobek *et al.* 2014). Combining the building material consumption with supply chain databases helps to complete a life cycle wood flow analysis (LCWFA) downstream of the supply chain. Moreover, by doing so, it is possible to understand the potential of a sector regarding the supply chain capacity and resource availability. This is important because the competition between products and sectors affects the resource availability and thus the environment and sustainability (Mantau 2015).

Objective

To the best of the authors' knowledge, studies have been mainly focused on residential buildings. This is mainly due to the data availability such as the average square meter per capita and the MCI. Few researchers have focused on NR buildings at a large scale, mainly due to a lack of data. Therefore, the objective of this paper is to propose a methodology to build an inventory of NR buildings wood consumption. The authors aim at exploring the effect of the parameters and what their range can represent on the estimation. Such methodology will help give an estimation of the amount of structural wood products in new NR buildings, and build a wood flow analysis downstream of the supply chain. This work is further dedicated to a life cycle assessment (LCA) of structural woods in non-residential buildings at a large scale, and to a LCWFA at a regional scale.

METHOD

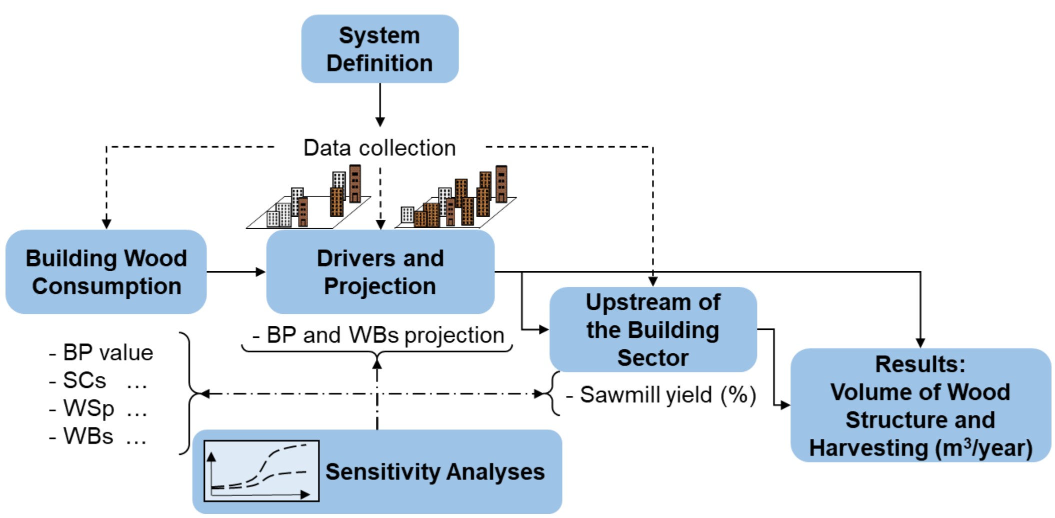

Fig. 1. Overview of the suggested methodology (with BP standing for the building permits for new constructions, SCs for the structural cost share, WSp for the wood structure price, and WBs for the wood building share)

The following subsections explain in more details the proposed methodology. All the results were obtained using an Excel parametrized master file.

System Definition

Quebec is the geographical boundary of the building sector. The period from 2010 to 2050 is the temporal boundary of the harvesting wood demand for the new NR building structures. The system includes the stages of harvesting, transforming (1^{st} and 2^{nd}), and manufacturing of structural products. These stages consider the softwood structural products such as cross-laminated timber (CLT), glued-laminated timber (Glulam), or roof frame. The material losses during the first transformation in the sawmills are included, and only the softwood is considered.

Building Wood Consumption

The aim is to present a methodology to estimate an inventory of NR buildings stock whose concept and parameters are extracted and adapted from Geskin Conseil (2008). This methodology is applied to the structural wood products in NR buildings. Following the idea of Eq. 1, Eq. 2 presents the relation between parameters that scale the amount of a material used per unit of structure up to the regional scale,

$$Estimation\ of\ structural\ wood\ (m^3) = \frac{BP\ (\$) * SCs\ (\%) * WBs\ \ (\%)}{WSp\ (\frac{\$}{\mathrm{m}^3})} \qquad (2)$$

where the parameter *BP* is the value of the building permits of new NR buildings ($). It aims to represent the spending and the size of this sector, *SCs* is the structural cost share (%), *WBs* is the wood building share, and *WSp* is the wood structure price ($/m^3). The elaboration of a building permit form comes when there is an intention to build (Geskin Conseil 2008; Statistics Canada 2019a) that tends to materialize. Indeed, building permit data serve as a leading indicator for the construction industry because obtaining a building permit is one of the first steps in the construction process. It is also a major input of expenditures by companies and governments for building construction (Statistics Canada 2019a) and strongly correlated with the investments in NR construction ($R^2 = 0.9$ is obtained when the analysis was performed; more details are available in the supplementary information (Fig. S1; Statistics Canada 2018a, 2019b)). Building permit value ($) (Statistics Canada 2019b) does not include investments such as architectural, engineering (*e.g.*, water, sewer, and drainage works), legal fees, and construction site preparation (Statistics Canada 2018b). Thus, it is only close to the building value and not the actual perceived full value. The estimations consider the building permits for new buildings and additional structure to an existing building.

The values of the building permits consider the construction cost. The cost of the structure share *SCs* is the parameter to consider when estimating the cost of the structure in comparison with the total building cost. Existing NR buildings reported in public (CECOBOIS 2012, 2013; Beaucher 2014, 2015, 2017; Beaucher *et al.* 2018) and confidential reviews (on behalf of the Ministry of Forests, Wildlife, and Parks) (Lamothe 2015) allow the definition of an average value of *SCs*. Case studies of the confidential report include NR buildings, representing Quebec public building context.

Afterwards, the structure cost is converted into a wood quantity with *WSp,* the price of installed wood structure in the building ($/m^3). Existing case studies (CECOBOIS 2012, 2013; Beaucher 2014, 2017; Beaucher *et al.* 2018) helped to estimate this parameter. They presented the price of the installed structure and the amount of wood in the structure.

The third parameters presented above (*BP*, *SCs*, and *WSp*) helped to determine the quantity of wood installed in all new buildings. However, the wood structure is not employed for all NR buildings. As depicted by a survey (on behalf of Cecobois), engineers and architects reported that approximately 28% of their new constructions (4 stories and less) use wood structures (Robichaud 2017). Therefore, the coefficient *WBs* considers the share of new buildings that use wood structure.

Drivers Identification and Projection

The estimation of future amounts of wood in structures uses the same equation as the quantification of wood in current structures, but with scenario analysis and assumptions on the temporal evolution of each parameter. Thus, key drivers and their potential patterns are investigated using historical data, literature reviews, and industrial and institutional reports. The building permit values and the lumber costs follow historical trends. The share of the structural cost related to the building is constant, and the share of building with wood structure follows a sinusoid. Because the parameters of equation 2 evolve separately, the minimum and the maximum value of those parameters are used to simulate two extreme scenarios. More explanation on these projections follows.

In light of the correlation between the historical data of population (ISQ 2018) and total building permits ($R^2 = 0.918$), the authors made the projection of building permits according to existing minimum and maximum population predictions (ISQ 2019). Those predictions help to build a minimum and a maximum scenario. More details are available in the supplementary information (Figs. S1, S2).

The share of the structural cost among the building was assumed to be constant. Too few data are available regarding the year and type of building. As an emerging market in the province of Quebec, there is not enough information to understand how much its temporal variability is, compared to its variability according to the type of structure (or building). Moreover, because all monetary dollar values are increasing (the building permits and the price of the installed wood structure), it creates more inconsistency if the share of the structural cost is timely dependent.

Concerning the price of the installed wood structure, the average of the existing case studies was used and projected using the trend of softwood lumbers. The minimum and maximum values of the case studies were also projected.

Finally, the prospective approach to assume the building share with wood structure is exploratory. The authors used an S-curve shape, such as typical development (Hetemäki *et al.* 2014) for a minimum and a maximum scenario. It uses a sinus function as Eq. 3 depicts,

$$\boldsymbol{WBs}(t) = \left\{\frac{[\boldsymbol{WBs}(tF)-\boldsymbol{WBs}(t0)]}{2}\right\} * \left\{sin\left[\left(\frac{\pi}{tF-t0}\right) * \left(t-\left(\frac{to+tF}{2}\right)\right)\right] + 1\right\} + \boldsymbol{WBs}(t0) \tag{3}$$

where *WBs*(t) is the instantaneous share of new constructions that use wood structure at the time t (year), *WBs* (t_0) is the share at the initial calculation time t_0 (2017), and *WBs* (t_F) is the share at the final time horizon t_F (2050).

Upstream of the Building Sector

From the estimations of wood amount in the NR building structures, wood flows are followed-up throughout the supply chain until harvesting to evaluate the relative weight of the structural wood demand on the other demands. The supply chain starts at the harvested wood stage (the stumps and the extracted biomass during the harvesting are excluded). To do so, the last important parameter, which is also time-dependent, is the sawmill yield. It is the highest one among the supply chain of lumber because approximately 40% of roundwood is lost in processing standard lumber. Through official statistics (MFFP 2018a, b), the authors observed an improvement in the sawmill yields, which means an increase in lumber production and a decrease in the chips and the sawdust per cubic meter of roundwood. However, the wood barks per roundwood were rather constant in time. Thus, for the projection of flows, the trends were maintained. These trends may show the progressive installation improvements that the sawmills are doing to increase their efficiency. For example, they recover parts during trimming to transform them into smaller ones, they use thinner saws to make a smaller cutting thickness, and they use optimized multi-saw slitting machines - straight sawing and curve sawing (MRNFP 2004). However, because the lumber per roundwood cannot be equal to 1, the authors stopped the trends and supposed a constant value when one of the yields reached its minimum value according to the statistics databases (MFFP 2018a, b) and reports (MRNFP 2004). The minimum yield of roundwood per softwood lumber is 3.46 m^3/mbf (with mbf standing for the volume of the lumber in thousands of board feet) in the region of Chaudière-Appalaches (Canada) (MFFP 2018b). The yield of wood barks per roundwood is an exception because it was supposed constant at its historical minimum. With the database it was possible to assess each individual yield (of lumber and each of the by-products) throughout time. However, it was not possible to cross-check their interdependence due to the diversity in the yield units and the aggregation of wood species. Therefore, to make all the yield evolutions consistent, the authors balanced the volume of lumbers per roundwood and by-products per roundwood. To do this, when the lumbers per roundwood reaches its limit and stays constant for the following years, all by-products per roundwood also become constant. The sum of yields is equal to 100%.

Finally, to understand the potential of wood in NR structures compared to the resource to harvest and the evolution of other sectors, the state of other sectors is projected. The current overriding sector of domestic harvesting is lumber exportation. Thus, the projection of the current harvesting follows the export trend.

Sensitivity Analyses

As presented earlier, some parameters are available but their scopes do not exactly fit with the objective. To better fit with the scope and the system boundaries, the distributions of the different parameters (according to the type of buildings, the number of stories, the type of structures, and the share of materials) would contribute to better modeling. Because of the lack of data (not enough data, not existing data or not available, and transparent data) sensitivity analyses will follow. Table S1 helps to explain what effect the average value of the parameters may have on the results (the volume of wood products and of harvesting). Indeed, the average scenario may under-or-overestimate the results according to the scope that the parameters cover compared to the objective. At such a large scale, with such uncertain parameters, it is important to look at the main influencing parameters. In this section, Figs. 2, 3, 4, and 5 present the ranges of the parameters around their assumed average value. These allow for the study of the effect of each parameter and their contributions to extreme scenarios. Because the projections of parameters are also sources of uncertainties, they will be challenged.

The building permits survey is representative because it covers approximately 95% of the Canadian population in all regions. The remaining municipalities with 5% of the population are not represented, but their construction activities have little impact on the total (Statistics Canada 2019a). Moreover, the survey recently disaggregated the permits by type of work (Statistics Canada 2017). The category new constructions of buildings accounted for 40.5% of the total building permits, and the additional structures to existing buildings accounted for 12.5% of the total in 2018 (Statistics Canada 2019b). These shares, only available for 2018, are assumed constant for all years in the modelling. This constant shares of 53% (40.5% and 12.5%) was applied for the past data and the projection. The other categories of the type of work (Alterations, Improvements, Conversions, and Demolitions) are not new constructions needing new structures; thus they are not used for the estimation. Another fact on building permits is that the construction of one new building can include several permits (Statistics Canada 2017). This can overestimate the figures. In 2018, additional value to previous permit(s) accounted for less than 0.1% of the total building permits (Statistics Canada 2019b), so this share was assumed negligible. Because a correlation exists between the building permits and the population, the population scenarios (ISQ 2019) helped to draw extreme scenarios of building permits as illustrated in Fig. 2. The equation of the building permit projections is Eq. 4, with *i*, the type of the population projection (*i.e.*, maximum, average, and minimum population).

$$BP\ for\ new\ constructions_i = (0.405 + 0.125) * (population_i * 3.7236 - 2 * 10^7) \quad (4)$$

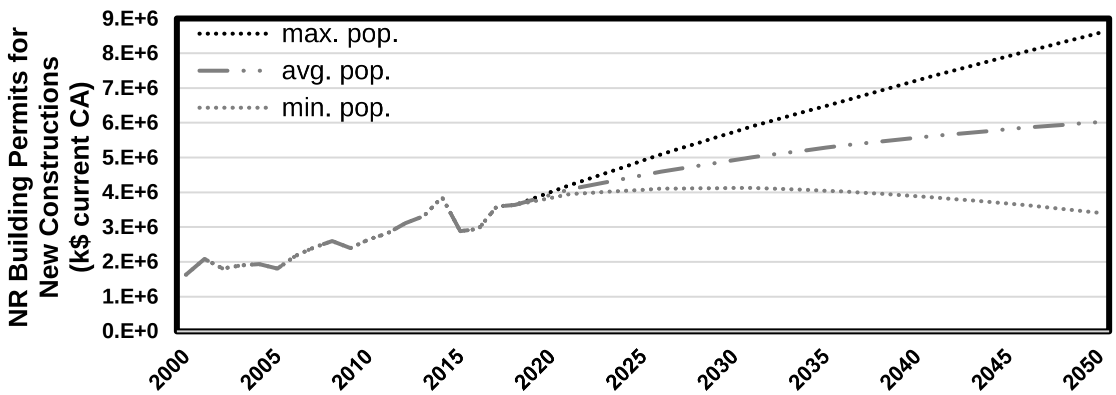

Fig. 2. Building permits of the new buildings and the structural additions to existing buildings (53% of the total); Historical values: Statistics Canada (2019b); Projections: correlated with population projections (ISQ 2019)

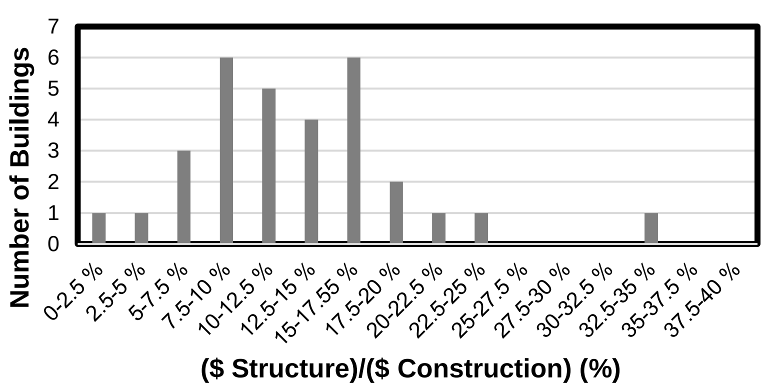

Fig. 3. Distribution of the *SCs*

Concerning the share of the *SCs* (Fig. 3), the authors elaborated on the distribution of the value using examples of available real case studies. Thus, the sensitivity analysis of this parameter considers the extreme values of this shape (min: 2.1%; average: 13%; max: 33.6%).

Some factors may influence the variability of costs, such as the building construction system (lightweight framing, glulam, CLT, or hybrid), its size (the span of the beams), the function of the building, the share of the other elements (if the building is mainly a structure), *etc.*

For the price per cubic meter of the wood structure, *WSp* (Fig. 4), it was assumed how much it is related to the softwood sawnwood to follow the sawnwood trend. The minimum and the maximum values of the case studies were also projected by following the trend of the sawnwood price per cubic meter.

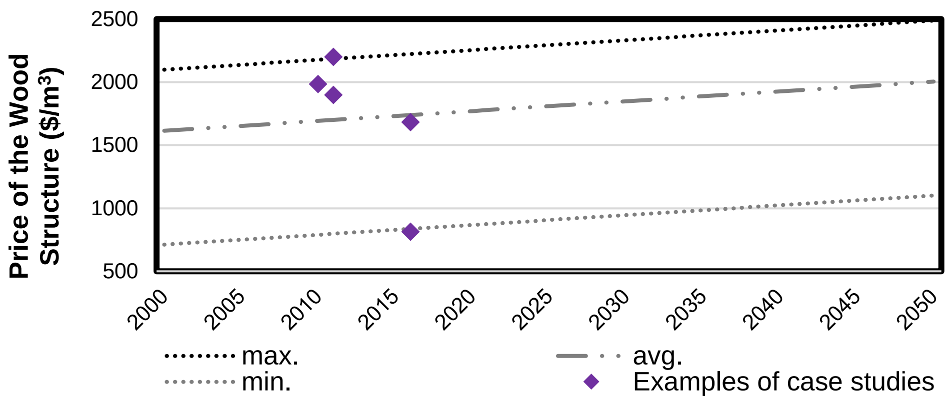

Fig. 4. Range of the example of the cost of a wood structure (WSp); Linear trend: FEA (2019); case studies: CECOBOIS (2012, 2013), Beaucher (2014, 2017), and Beaucher *et al.* (2018)

The share of new buildings with a wood structure, *WBs* (Fig. 5), comes from a survey that considers several parts of the structure (main structure, roof frame, and walls). The values are available for buildings with four stories or less. However, because of a lack of information on the distribution of buildings according to the stories, it was applied to all new building constructions. This implies an over-estimation of the wood amount in structures because the share is less for buildings higher than four stories (Robichaud 2017).

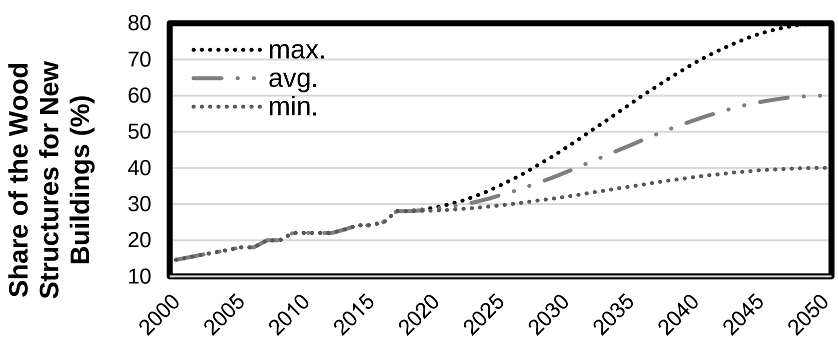

Fig. 5. Share of the wood structures for new buildings (WBs); Historical values: Robichaud (2017); Projections: s-curve scenarios (Eq. 3)

The most uncertain main parameters are the *SCs*, *WSp*, and the *WBs* because of the minimal available data, the type of the structures, the number of stories, *etc.* Another reason is their high range between the maximum and the minimum values.

RESULTS AND DISCUSSION

The first results (Figs. 6, 7, and 8) illustrate the estimated amount of wood in new NR building structures. The last results (Fig. 9) depict the total harvesting due to the additional demand for NR structures. Figure 9 allows for measurement of its related weight to other sectors demanding this resource. The results of the sensitivity analyses show just how much parameters can change and affect the results.

Building Wood Consumption

Wood in the structures of new NR buildings

Figure 6 displays the estimation of wood in the new NR building structures. The scenarios consider the average evolutions of the parameters *BP*, *SCs*, *WSp*, and the three exploratory scenarios (min., avg., and max.) of the *WBs*.

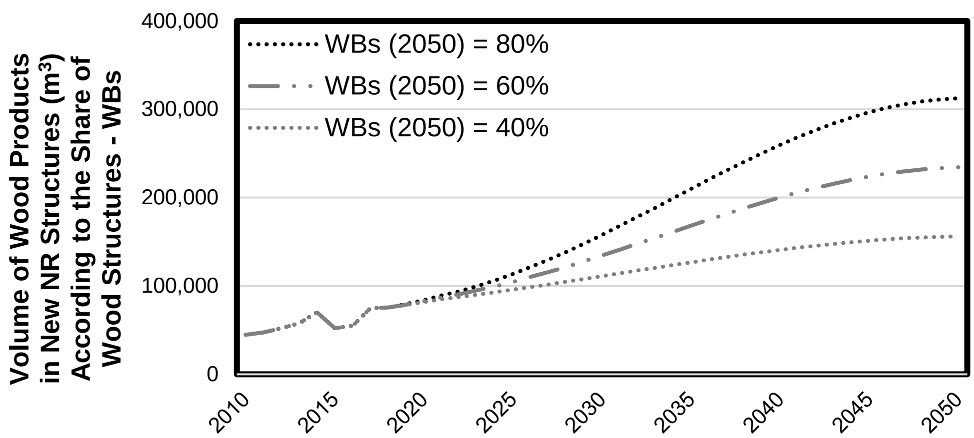

Fig. 6. Estimation of wood products (m^3) in new NR structures of buildings in Quebec (new buildings and structural additions to existing buildings)

There is consistency in the sense that when wood is more expensive, it may be used less. However, price is not related to other endogenous parameters such as the availability of the resource.

Sensitivity analyses

The previous paragraphs presented the results due to the parameters of Eq. 2, (*BP*, *SCs*, *WBs*, and WSp). Because of their uncertainties, the objective of this section is to present the sensitivity of the results due to each parameter. The effect of each parameter was studied when it changed by more or less a percentage of its value. Then, the more contributing parameters to the extreme scenarios were investigated. Finally, because projection methods are also sources of uncertainties, this issue was addressed.

First of all, it is clear that if any of one numerator of Eq. 2 is changed by +/- x% of its value, the results will be changed by +/- x% of its value. If the denominator is changed by +x% or -x% of its value, the results will be respectively multiplied $\frac{1}{1+x\%}$ or $\frac{1}{1-x\%}$. This means that whatever the sensitivity applied to the *BP*, the *SCs*, or the *WBs*, the effect on the result will be the same. Moreover, the sensitivity applied on the *WSp* will have an inverse effect (either higher or lesser), as summarized in Table 1 and illustrated in Fig. 7.

Table 1. Effect of Parameters on the Result

If	one numerator	is changed by	+ x%	then, the result is changed by	+ x%
			- x%		- x%
	one denominator		+ x%		- y% (|y| < |x|)
			- x%		+ z% (|x| < |z|)

Because there is only the wood structure price (*WSp*) at the denominator, it is the parameter that has the least influence when it increases and the most when it decreases (with the assumption that parameters are independent).

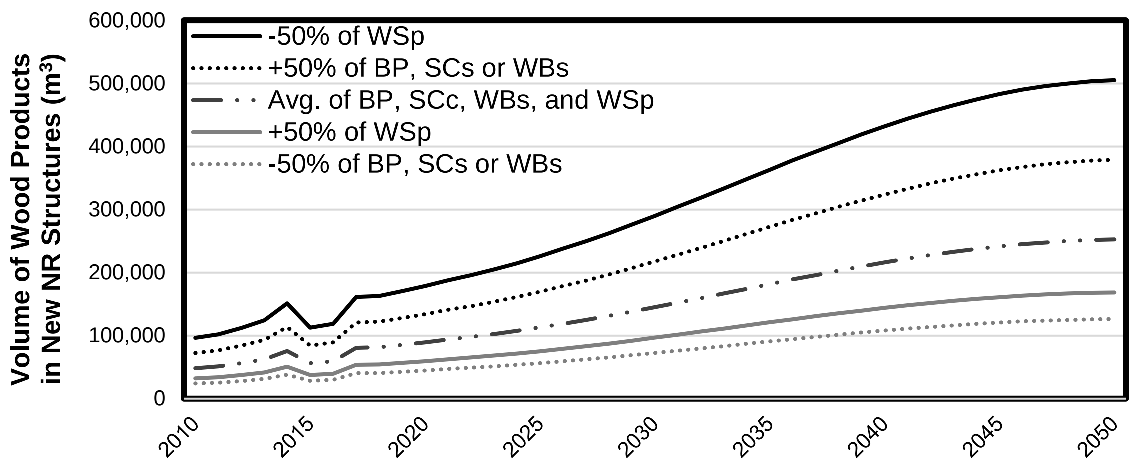

Fig. 7. Sensitivity of one numerator (BP, SCs, or WBs) and the denominator (WSp)

As presented above, numerators have the same contribution to the results related to their average. However, they do not have the same interval around the average. Moreover, the interdependency between numerators and denominators is not set. The following extreme scenarios helped to frame this limitation. Tables 2 and 3 show how much the extreme values of parameters contribute to the extreme scenarios.

Table 2. Effect of Extreme Values on the Result in 2017

2017	BP	is changed by	**+/-** 0%	then, the result is changed by	**+/-** 0%
	SCs		**+** 158%		**+** 158%
			- 84%		**-** 84%
	WBs		**+/-** 0%		**+/-** 0%
	WSp		**+** 28%		**-** 22%
			- 52%		**+** 107%
If all the numerators and the denominator are changed by opposite signs, the result is changed by:		- 87%	and	+ 435%	
If the numerators and the denominator are changed by the same sign, the result is changed by:		- 67%	and	+ 102%	

Table 3. Effect of Extreme Values on the Result in 2050

2050	BP	is changed by	**+/-** 43%	then, the result is changed by	**+/-** 43%
	SCs		**+** 158% **-** 84%		**+** 158% **-** 84%
	WBs		**+/-** 33%		**+/-** 33%
	WSp		**+** 24% **-** 45%		**-** 19% **+** 82%
If the numerators and the denominator are changed by opposite signs, the result is changed by:		- 95%	and	+ 795%	
If the numerators and the denominator are changed by the same sign, the result is changed by:		- 89%	and	+ 296%	

Table 3 shows that the share of structural cost in the construction cost (*SCs*) is the parameter that implies the most uncertainty on the results because of its high variability. It influences the result between - 84% and + 158% of its average scenario.

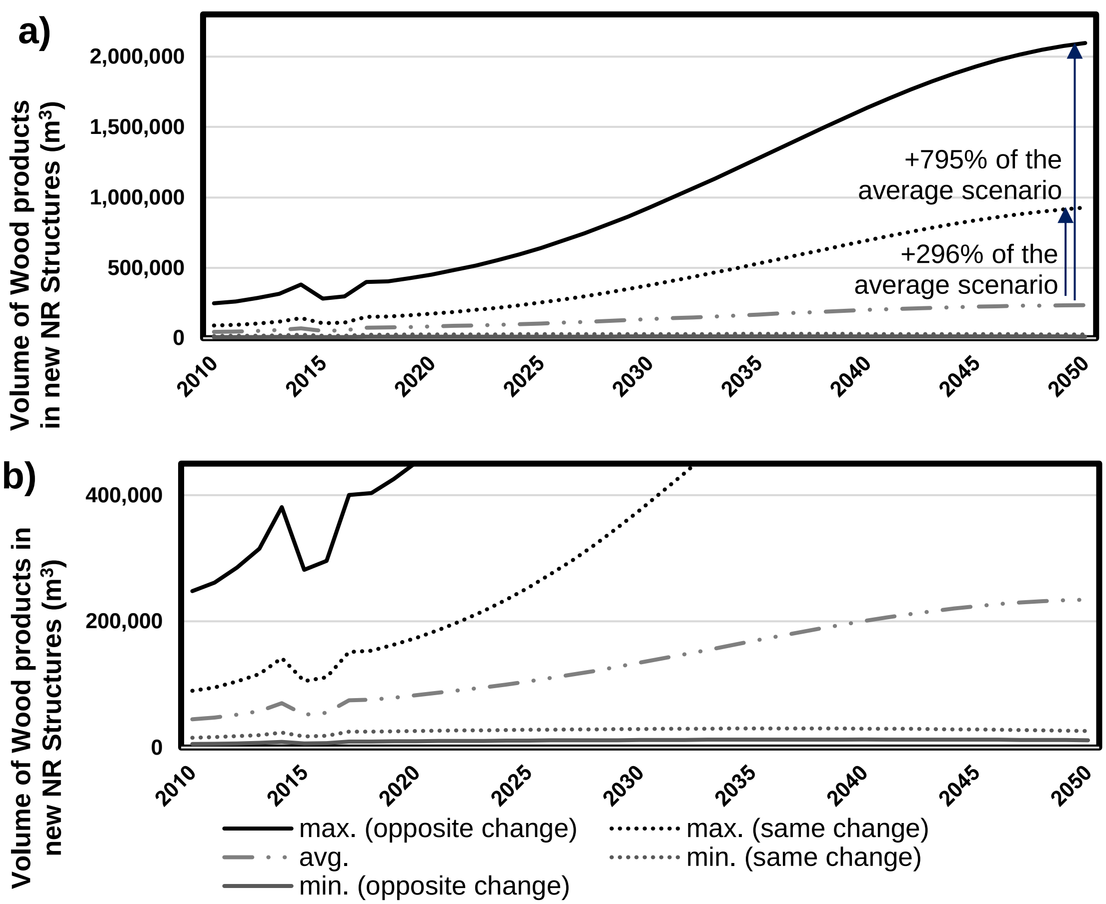

Fig. 8. Extreme scenario of wood (m^3) in the structure of new NR buildings in Quebec (new buildings and structural additions) – according to the change of numerators and denominators compared to the average scenario: a) all curves and b) zoomed in for the average and minimum curves

Figure 8a shows the highest uncertainties. An increase of approximately + 795% of the average scenario in 2050 is depicted (up to 2,096,640m^3). This result is due to the maximum values of the numerators (*BP*, *SCs*, or *WBs*) and the minimum value of the denominator (*WSp*).

For the projections, some parameters follow exploratory scenarios such as the *WBs* and the *BP*. They respectively follow the arbitrary scenarios and exploratory scenarios of the population (ISQ 2019). The projection of these parameters was also performed according to their respective historical trend. This was to assess the sensitivity of the projection methods on the results. The sawmill yield follows its historical trend but, depending on the amount of included past data, the trend has different growth coefficients.

In supplementary information, projecting the trend of the *WBs* will result between the average and the minimum exploratory scenario (Fig. S3 and Table S2). For the projection of the *BP*, the trend is between the maximum and the average scenario of the building permit (Fig. S4 and Table S3). *WBs* and *BP* trends stay between the maximum and minimum projection. Concerning the projection of the sawmill processing yield, the trend is not the same when the included data relate to the years from today to 2008 or to 1990. It will result in different volumes of roundwood to harvest between the starting and the ending date. The maximal difference is at 11% (around 2028 – Fig. S6).

Upstream of the Building Sector

The graph below (Fig. 9) displays the historical availability of softwood in the forests of Quebec, the total harvesting (NFD 2018), and the historical harvesting of softwood for lumber exports (NRCAN 2019). It also depicts the projections after 2017. The total harvesting considers the four sectors of the wood industry (pulp, paper, and cardboard; the sawmill industry; veneers, plywood, and panels; and finally, the cogeneration and energy products industries).

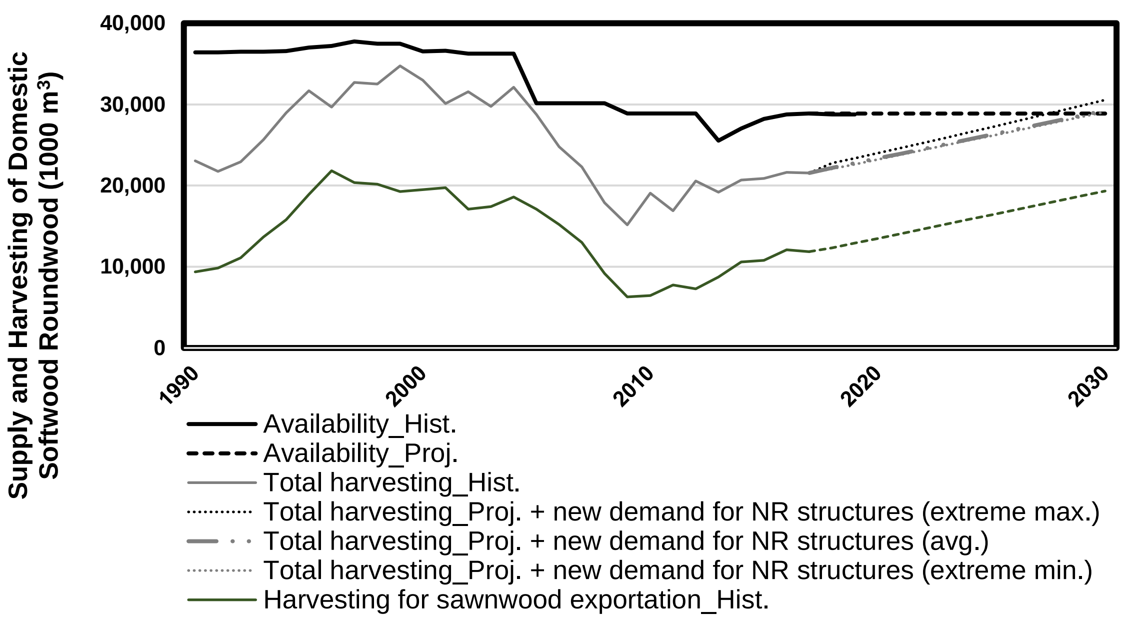

Fig. 9. Total domestic softwood harvesting for NR building related to the availability and others projected end-uses (thousand of m^3); Historical values of total harvesting and availability from NFD (2018), and historical values of harvesting for sawnwood exportation converted from NRCAN (2019)

Regarding the other markets, the importance of the additional softwood roundwood harvesting for NR building structures does not override the total harvesting. The trend of the total harvesting remains more important than the estimations for new NR structures (estimations with the maximal range of the Fig. 8a). In 2030, even with high uncertainties in the estimation of wood in new NR building structures, its harvesting respectively accounts for 0.07%, 0.75%, and 4.95% of the total harvesting in the extreme minimum, average, and extreme maximum scenarios (under the assumption that the other markets follow the trend of the exportation). The softwood lumber exports accounted for approximately 50% of the total harvesting in the last 10 years and mainly drives the past harvesting trends. It implies the harvesting for new NR structures may not be the main market branch that will contribute to reaching the limit before 2030 (for the time horizon of 2050). More disaggregation between the different wood products is necessary to understand if competition between them will occur to allow the growth of their respective market. This is important because the competition between products and sectors affects the resource availability and thus the environment and sustainability (Mantau 2015).

The sensitivity that was performed on the yield (Fig. S5) influences the roundwood to harvest (Fig. S6). This effect accounts for a maximal difference of 11% between the two harvesting curves for NR structures in 2028. Regarding the total harvesting, this difference is not remarkable (*i.e.*, a difference of less than 0.05% of the total harvesting in 2028).

Discussion

The research aimed at investigating a methodology to account for the NR building material consumption. The presented method was applied to estimate the volume of wood in the structures of the new non-residential buildings. Then, projections of the estimation were suggested according to three scenarios (min., avg., and max). The importance of the estimation was also assessed comparatively to the total harvesting of all the wood sectors. The sensitivity analysis highlighted the parameters with the most influence on the results and with the highest ranges of uncertainty. In future works, system boundaries should be expended to understand the effects of wood products consumption on the other structural materials as well as the effects of the stock accumulation on future discarded material.

In the literature, to estimate the material consumption, dynamic material flow analyses mainly considered the material intensity per square meter and statistical data on the total floor area put in place (or the material intensity per capita and the population of the country). Therefore, the presented methodology to estimate the quantity of wood should be compared to other methods using those parameters (under the condition of available data).

Finally, this method can serve, on one hand, for life cycle inventory to evaluate the environmental impact of a growing wood product use in the NR buildings. On another hand, it can also serve to initiate a life cycle wood flow analysis. However, to improve the results, more research on the material composition of the non-residential building archetypes is necessary.

CONCLUSIONS

1. Regarding the estimation of wood for new NR building structures, the average scenario (*WBs* 2050 = 60%) suggested an increase of 159,513 m^3 from 2017 to 2050. It is 3.1 times higher than the volume that was estimated for 2017 (74,801 m^3). The maximum scenario is 4.2 times higher and the minimum scenario is 2.1 times higher (Fig. 6). However, the uncertainties in the parameters showed higher values (2,096,640 m^3 of wood in structures, approximately + 795% of the average scenario in 2050).

2. The results showed how and when the resource availability can be constrained depending on the assumption of the projections in the wood use markets. If all harvestings follow the export trend, the resource availability can be constrained before 2030, considering or not the harvesting for new NR building structures. Despite the high uncertainty in the amount of wood in NR building structures, the estimation has a small weight on the total harvesting. In 2030, it accounts for 0.07%, 0.75%, and 4.95% of the total harvesting in the extreme minimum, average, and extreme maximum scenarios (under the assumption that the other markets follow the trend of the exportation).

3. The main sources of uncertainty in the estimation of wood in the structures of new NR buildings are the interdependency between parameters of the model, in addition to used parameters to estimate the structure price. Regarding the softwood harvesting, one of the main sources of uncertainty concerns the evolution of the NR market in comparison to others markets that use the same resources (such as wood exportations, papers, *etc.*). This can be an issue as all markets contribute to reaching the limit.

ACKNOWLEDGMENTS

The authors are grateful to the Natural Sciences and Engineering Research Council of Canada for the financial support through its IRC and CRD programs (IRCPJ 461745-18 and RDCPJ 524504-18) as well as the industrial partners of the NSERC industrial chair on eco-responsible wood construction (CIRCERB). Older versions of some figures will be published as a proceeding in an IOP Conference Series as: S. Cordier, F. Robichaud, P. Blanchet, and B. Amor (forthcoming) "Enhancing consistency in consequential life cycle inventory through material flow analysis," *SBE19 Sustainable Built Environment Conf. Session Building Design 5: LCA Challenges: Consequential LCA and Uncertainty.* Regarding the conferences series copyright and permission, all of the conference series articles are currently published under a CC BY license (*i.e.*, it is free to share — copy and redistribute the material in any medium or format. It is also free to adapt — remix, transform, and build upon the material for any purpose, even commercially). The figures and text are modified in the paper and updated with new data and new sensitivity analyses.

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Article submitted: August 13, 2019; Peer review completed: October 26, 2019; Revised version received: December 6, 2019; Accepted: December 7, 2019; Published: December 11, 2019.
DOI: 10.15376/biores.15.1.787-813

APPENDIX

SUPPLEMENTARY INFORMATION

The Building Permits

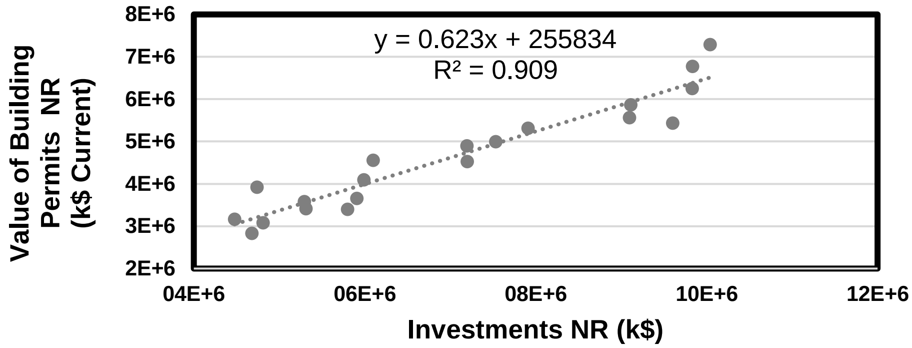

Fig. S1. Correlation (1997 to 2017) between the total building permits (Statistics Canada 2019b) and the Investments (Statistics Canada 2018a)

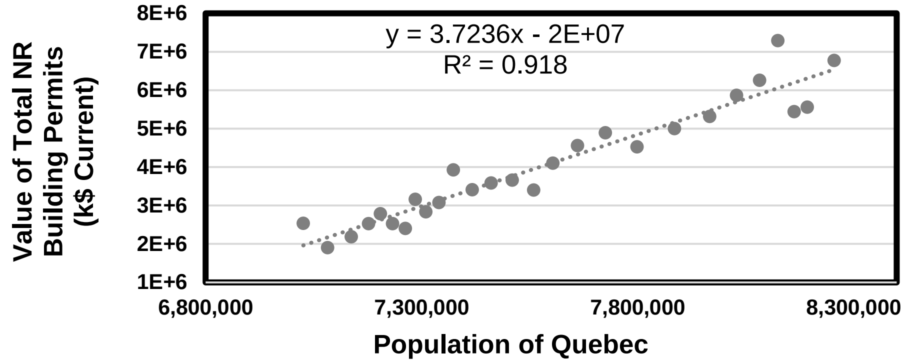

Fig. S2. Correlation (1991 to 2017) between the total building permits (Statistics Canada 2019b) and the population (ISQ 2018)

Due to the correlation between the historical data of population (ISQ 2018) and building permits, the authors used the existing projections of the population (ISQ 2019) to project the building permits according to three scenarios (minimum, average, and maximum). To do so, the total value of building permits (new constructions, alterations, improvements, additional structures, conversions, demolitions) follows Eq. S1 displayed by Fig S2. The total *BP* is only dependent on the population,

$$Total\ BP_i = population_{\ i} * 3.7236 - 2 * 10^7 \tag{S1}$$

with *i* corresponding to the maximum, average or minimum scenario of the population projection. Then, the projection of the total value of building permits (new constructions, alterations, improvements, additional structures, conversions, demolitions) helped to project the BP for new constructions (Eq. S2). But, to extract the value of building permits for new constructions, the authors used the share of the total building permit which accounts for new building constructions (40.5% of the total) and additional structures to existing buildings (12.5% of the total). The building permits for new building constructions and additional structures (Fig. 2.) follow Eq. S2:

$$BP\ for\ new\ constructions_i = (0.405 + 0.125) * (population_{\ i} * 3.7236 - 2 * 10^7) \tag{S2}$$

Analysis of the Average Estimation

Table S1a. Effect of Average Value of Parameters – From the Value of Building Permits to the Value of New NR Building Constructions

Scope of the Objective	**Building permits** *BP* - Statistics Canada (2019b)			Share of New Building Constructions and Additional Structures			**Value of New NR Building Constructions**	
	($)	Comments		(%)	Comments		($)	Comments
All ICI	yes			yes			yes	
All Stories	yes			yes			yes	
All New Constructions	o.e.	It considers several types of works (new constructions, alterations, improvements, additional structures, conversions, demolitions).	x	**yes**	**New permits of new constructions**	=	Yes	In the “new constructions” category there are New construction, Foundation, Superstructure or part of a new building, Mechanical, Installation of a pre-fabricated building, Additional value to previous permit(s). So, there will be still a bit **over-estimation** of the values of the new NR buildings.
Structure Only	o.e.			o.e			o.e.	
- Wood	yes			yes			yes	
- Other Materials	yes			yes			yes	

o.e.: over-estimation

Table S1b. Effect of Average Value of Parameters – From the Value of New NR Building Constructions to the Value of New NR Structures

Scope of the Objective	**Value of New NR Building Constructions** ($)	Comments		Share of Structure in the Construction Cost *SCs* (if all were in wood) - CECOBOIS (2012, 2013); Beaucher (2014, 2015, and 2017); Beaucher *et al.* (2018) and Lamothe (2015) (%)	Comments		**Value of New NR Structures** ($)	Comments
All ICI	yes			yes	There are few industrial buildings in the examples, but the ICI building permit shares are approximately 20% for Industrials, 53% for Commercials, and 27% for Institutional (from 2000 to 2017) with a constant trend from 2000 to 2017 (Statistics Canada 2019b).		yes	
All Stories	yes		x	**no (1 to 3)**	The examples are for 1 to 3 stories, but it does not seem to depend on the number of stories only. The building cost and the structural cost can both depend on the number of stories, but the authors have too few examples to understand if the ratio of those costs is independent of the stories.	=	**yes**	Assuming it is independent of the stories.
All New Constructions	yes			yes	Considers construction year > 2009. Does not seem to depend on time.		yes	
Structure Only	o.e.			**yes**	Considers the ratio “wood structure cost” / “construction cost”.		yes	
- Wood	yes			**yes**	It considers the buildings with wood as the main structural element.		**o.e.**	**o.e. if the wood structure is more expensive than other structural materials.**
- Other Materials	yes			**no**	Few other materials exist in the structures of the cases studies.			

o.e.: over-estimation

Table S1c. Effect of Average Value of Parameters – From the Value of New NR Structures to the Volume of Wood in All New NR Structures

Scope of the Objective	**Value of New NR Structures**			Structural Cost per Cubic Meter of Wood Products *WSp* - CECOBOIS (2012, 2013); Beaucher (2014, 2017); Beaucher *et al.* (2018)			**Cubic Meter of Wood Products if Applied to All New NR Structures**	
	($)	Comments		($/m^3)$^{-1}$	Comments		(m^3)	Comments
All ICI	yes			yes			yes	
All Stories	yes		x	**no (1 to 3)**	The examples are for 1 to 3 stories. It may be assumed this parameter depends on the number of stories (and the loads). With more stories, the load applications can be higher, implying a higher value ($/m^3). So, this parameter value can be under-estimated, implying an **over-estimation** of the cubic meter of wood products.	=	o.e.	u.e. of the ($/m^3)$^{-1}$ implying o.e. of the (m^3).
All New Constructions	yes			yes	Considers construction year > 2009. Does not seem to depend on time.		yes	Assuming it is independent of the stories.
Structure Only	yes			yes			yes	
- Wood	o.e.			**yes**	Figures of examples consider only wood products.		o.e.	It is like all the ICI structures were using wood.
- Other Materials				**no**				

o.e.: over-estimation; u.e.: under-estimation

Table S1d. Effect of Average Value of Parameters – From the Volume of Wood in All New NR Structures to the Volume of Wood for A Share of NR Buildings

Scope of the Objective	Cubic Meter of Wood Products Applied to All New NR Structures			Share of Wood Building *WBs* - Robichaud (2017)			Cubic Meter of Wood Products Applied to A Share of New NR Structures – Fig. 6	
	(m^3)	Comments		(%)	Comments		(m^3)	Comments
All ICI	yes			yes			yes	
All Stories	o.e.			**no (1 to 4)**	Currently, the share of high-rise buildings with wood structure is less than the one for 1 to 4 stories. So, applying the value of 1 to 4 stories buildings for all the new buildings implies an **over-estimation** of the cubic meter.		o.e.	
All New Constructions	yes		x	yes	Considers recent buildings.	=	yes	
Structure Only	yes			**Not all structural parts**	The main structure and the roof frame (for buildings with 1 to 4 stories) have the highest share of wood than other structural elements (such as exterior and interior walls and other lightweight frames). So, applying the value of the main structure for all parts of the structure implies an **over-estimation** of the cubic meter.		o.e.	
- Wood	o.e.	It considers all the new ICI structures use the wood.		**yes**	This coefficient considers the current share of wood structures for new buildings.		yes	
- Other Materials	No			**yes**			//	

o.e.: over-estimation

Table S1e. Effect of Average Value of Parameters – From the Volume of Wood for a Share of NR Buildings to the Harvesting

Scope of the Objective	**Cubic Meter of Wood Products Applied to a Share of New NR Structures – Fig.6**			Yield Processing - MFFP (2018a)			**Cubic Meter of Harvesting**	
	(m³)	Comments		(%)	Comments		(m³)	Comments
All ICI	yes			//			yes	
All Stories	o.e.			//			o.e.	
All New Constructions	yes			yes	This parameter is a function of time.		yes	
Structure Only	o.e.		x	**No (Sawn-wood only)**	Not all the structures only use sawn-wood. Some structural wood panels can use destroyed or laminated roundwood. Almost all a roundwood serves at manufacturing those structural wood panels without producing by-products (chips and sawdust). It means that the overall equivalent yield processing for all the type of structural wood products is under-estimated. It implies an **over-estimation** of the required roundwood to harvest.	=	o.e.	The under-estimation of the yield process implies an over-estimation of the required roundwood to harvest.
- Wood	yes			yes			yes	
- Other Materials	//			//				

o.e.: over-estimation

Sensitivity Analysis of the Projections

Projections of the wood building share and the building permits

Both projections of the trend of the wood building share (*WBs* – Fig. S3 and Table S2) and the building permits (*BP* - Fig. S4 and Table S3) will result between the maximum and the minimum exploratory scenario.

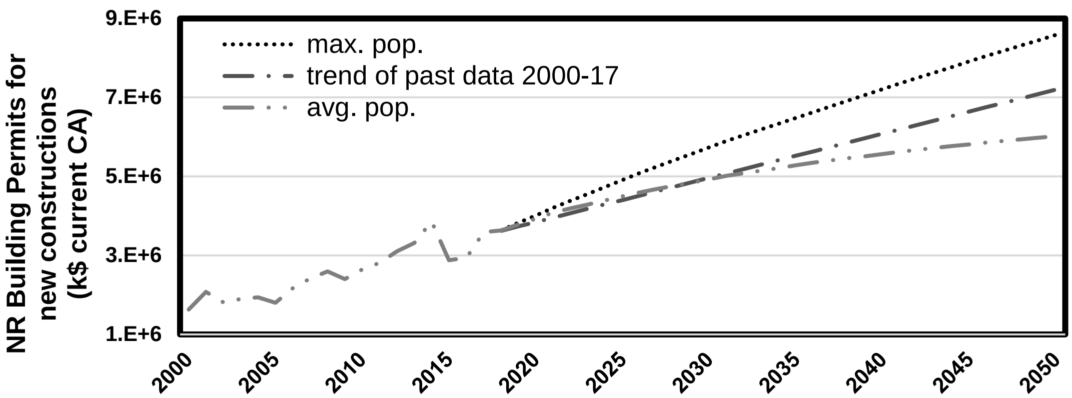

Fig. S3. Sensitivity of the building permits (BP) projections (value for the new buildings and the structural additions to existing buildings - 53 % of the total; Historical values: Statistics Canada (2019b))

Table S2. Effect of Projection of the BP

2017	The projection of the BP (following its trend)	is changed by	**+/-** 0%	compared to the projection related to the population. Then, the result will change by	**+/-** 0%
2050			**+/-** 20%		**+/-** 20%

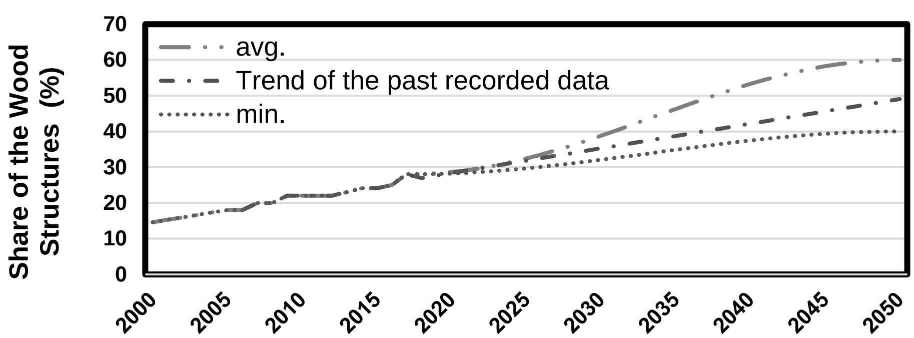

Fig. S4. Sensitivity of the share of building with wood structures (WBs) projections (Fig. 5 modified). Historical values: Robichaud (2017); Projections: s-curve scenarios and historical trend

Table S3. Effect of Projection of the WBs

2017	The projection of the WBs (following its trend)	is changed by	**+/-** 4%	compared to the projection related to the population. Then, the result will change by	**+/-** 4%
2050			**+/-** 18%		**+/-** 18%

Projection of the sawmill processing yield

For the sawmill processing yield, whatever the used range of data for projecting the tendency is, there is no effect on the demand of roundwood to harvest at the first year of projection and the final time horizon. Indeed, both trends reach the limit yield before 2050 (Fig. S5). However, it will result in different roundwood to harvest per sawnwood between the first and the final years.

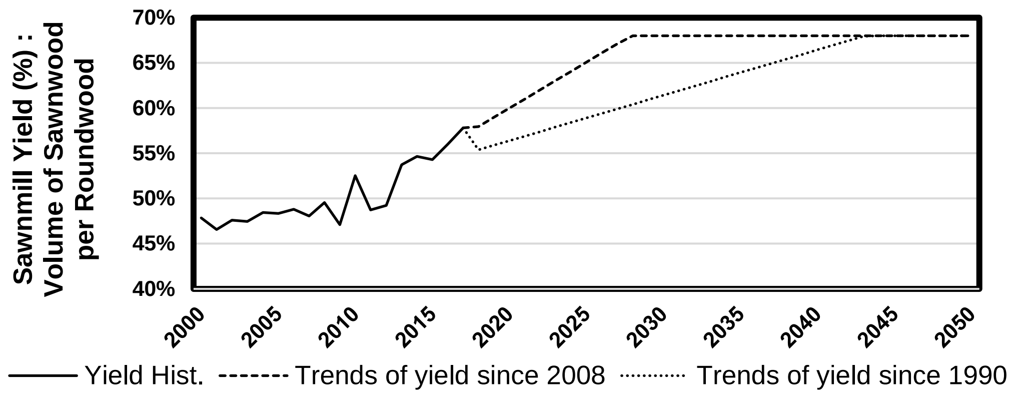

Fig. S5. Difference between the trends of sawmill yield since 1990 and 2008; Historical value of the sawnwood per roundwood elaborated from MFFP (2018a)

The historical values were estimated by doing the ratio between the statistics of sawnwood (mbf) and roundwood (1000 m^3) and by converting the mnf in m^3 with the conversion factor (2.36 m^3/mbf) of the source of the statistics (MFFP 2018c).

Figure S6 presents the sensitivity of the roundwood to harvest (ratio between the Figs. S5 and the extreme scenarios of fig 8a) -opposite changes). Indeed, the trend of the sawmill processing yield is not the same if the included data relates to the years from today to 2008 or to 1990. Figure S6 shows that, for each scenario, the maximum difference between the curves with trends since 1990 and 2008 is around 11% in 2028.

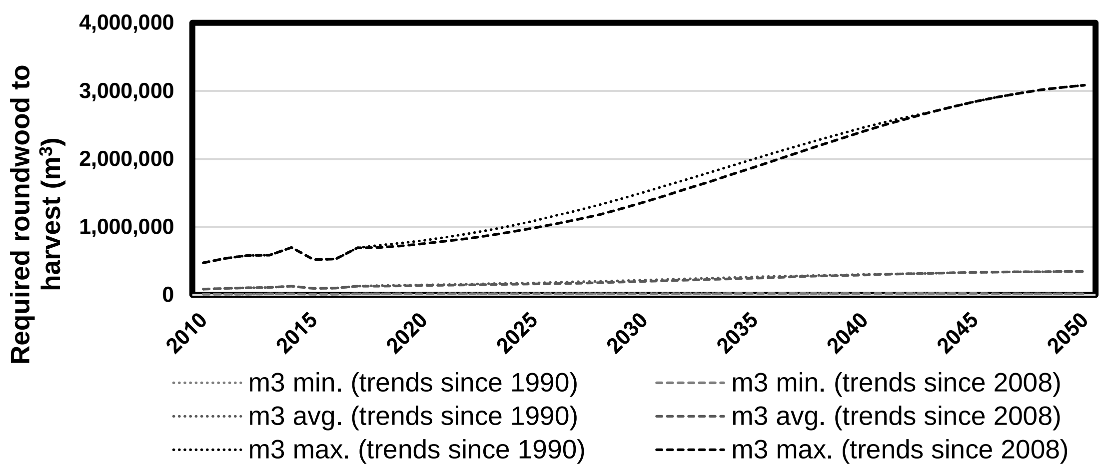

Fig. S6. Sensitivity of the roundwood to harvest for the new NR structures