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Enhancing consistency in consequential life cycle inventory through material flow analysis

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Abstract. Wood products are gaining interest in the building sector, due to their potential in sequestering greenhouse gas emissions. However, increasing wood materials use in the built market can have unforeseen changes in the material supply chains. Consequential Life Cycle Assessment (CLCA) allows the assessment of changes in material supply chain. To quantify and link those consequences, the affected physical flows need to be estimated. Material Flow Analysis (MFA) can bring to CLCA modelling more representative and quantitative information than the commonly used hypothesis in consequential modelling. Indeed, MFA considers physical constraints (technology performances and material availability), in addition to account for mass balance. The main objective of this presentation is to illustrate how such consistency is added to CLCA through an MFA of wood products in non-residential (NR) buildings in the province of Québec (Canada). Wood flows are tracked to identify their end-use markets and trends in consumption. To overcome the lack of data and bring insights on the sector's dynamics, such as stock variations and potential discarded flows that supply recycling markets, residence time model and also extrapolation and correlation between physical and economic parameters are used. Results show how flows can increase in the market before reaching their physical constraints, such as the available wood stock in the forest. These insights will significantly enhance the data collection for CLCA. In conclusion, the MFA brings support to CLCA by proposing a framework to model changes in the construction market.

1. Introduction

The consequential approach aims at modelling environmental impacts of the changes in the market due to a decision. Several methods exist to identify these changes [1]–[3], which all require an understanding of the market and flows. Indeed, the affected flows in the market depend on their expected sensitivity to the changes. But this requires different hypotheses on the state of the market before and during the changes. However, such characterization of the market is still a challenge for the development of consequential methodology in LCA. Indeed, for long-term assessments, assuming constant technological data is not sufficient, and data projection is required to build consistent prospective scenarios [2].

Recently, the consequential LCA approach started to be combined with the Material Flow Analysis (MFA) method, in order to build a system-wide inventory of flows associated to a given economic sector. Indeed, using MFA allows to track physical flows in the economy throughout their life cycle, including the end of life and exports [4]–[11]. Several studies showed MFA inflows and outflows (such as raw materials, finished products, old scraps, residues, and recycled materials) can provide information about both the dependence of a regional economy to some resource and its resource recovery potential [12]. Moreover, this tool brings insight into the dynamic flows of a sector. It helps to assess how important the market under study is regarding all the market and its physical constraints.

The MFA is a transparent tool that brings insight into the sector's dynamics. The Québec province is a good example because a political initiative projects to increase the use of wood in the NR buildings and no consistent and homogeneous accounts for engineering wood products (EWP) life cycle exist. The aim of this paper is to evaluate the state of the wood structural market for Non-Residential (NR) buildings by performing a material flow analysis of the EWP in the non-residential wood building sector. We then project scenarios to evaluate the potential consequences related to the growing EWP use. Dynamic MFA is expected to help in identifying and generating consistent flow and to capture trends in the market.

2. Method

The Quebec region is the geographical boundary of the NR building sector. The temporal boundary of the sawnwood demand, for the structure of new NR buildings, includes the 2010-2050 period. The system contains the stages of domestic harvesting, transforming (1st and 2nd), manufacturing of structural products, and using those products. These stages consider the softwood structural products which can represent cross-laminated timber, glued-laminated timber, or roof frame. The material losses from the first transformation are included.

The methodology to quantify the wood in the NR building structures is a top-down approach. Firstly, it defines the building sector at an aggregated level, with in our case, the value of the building permits. Secondly, to disaggregate this sector and get an amount of wood, we combined several parameters such as the share of the structure in the building cost, the price of a wood structure and the share of the building containing a wood structure. To match numerous inconsistent databases, the data reconciliation method in the MFA tool is performed with STAN software [13].

2.1. Quantifying the wood

The estimation of wood in the NR construction market (equation 1) implies several parameters extracted and adapted from Geskin Conseil [14]. The following equation presents the used parameters:

$$\frac{BP\ (\$) * \mathrm{SCs}\ (\%) * \mathrm{WBs}\ (\%)}{WSp\ (\frac{\$}{\mathrm{m}^3})} \tag{1}$$

The first parameter ***BP*** is the value of building permits. It can represent the spending and the size of the NR construction market at an aggregated level. Indeed, building permit data are used as a leading indicator for the construction industry since getting a building permit is one of the first steps in the construction process and is a major input of expenditures by companies and governments to build buildings [[15]–[17]]. However, the values ($) of the building permits are disaggregated to consider the value of the new building constructions among all the types of work such as improvements, conversion, addition. The scenarios only consider the building permits for new buildings with two scenarios (a maximum and a minimum).

Among the value of a building, the share (%) of the structural cost ***SCs*** (material and installation) in the total building cost (associated with the building permit) is necessary to consider the structure. We determined this share with several case studies from public [18] and confidential review (on behalf of the Ministry of Forests, Wildlife and Parks) [19] on the NR buildings whose structure is made of wood. The case studies of the confidential report are selected from a collection of hundred wooden buildings to meet the needs of ensuring the representativeness of the Québec public building context and to

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guarantee a coherence of the whole despite the many uses of wood for construction. The criteria consider the year of construction, the 100% wood structure, the building classification (recreation, sport, culture, education, health, offices and warehouses), the diversity of building vocations and the potential reproducibility of the project [19].

In order to convert the dollar values into the amount of wood, we introduced ***WSp*** the price of installed wood structure ($\$/m^3$) in the estimation. This is important to consider this price instead of the one of softwood lumber because the wood products are gaining value throughout the transformation chain from the sawmill to the building, which increases the price per cubic meter. Therefore, we avoided overestimation of the wood cubic meter installed in the NR buildings.

Finally, some buildings have a wood structure, not all. Therefore, we applied the coefficient ***WBs*** to consider the share of buildings using wood. It is this share which drives the modelling of wood consumption in NR buildings. Currently, around 28% of new NR buildings (4 stories and less) are using wood structure according to a survey (on behalf of cecobois) conducted with engineers and architects [20].

2.2. Projecting the quantification of the wood

We estimated a minimum and a maximum scenario of potential wood use in NR structure until 2050, according to the minimal and maximal parameters' values. The 2050 as a long-term horizon is set because of the estimated growing population after 2050 [21], suggesting there will be still a need for construction. Moreover, depending on the current market volume, a short-term analysis would not reflect consistent and significant effect because of the inertia of the market and the barriers. For future work, the buildings have a long lifetime (more than 50) and the future discarded flows of buildings would start to appear after these 50 years. This will involve a future secondary wood resource supply. The respective estimations of parameters are described below. The projection is made for each year in order to track changes between the starting calculation date (i.e. the time of the starting decision or change) and the final state. The idea is to follow the flows to understand if there might be intermediaries' consequences during the change modelling.

2.2.1. Demand of wood in the NR buildings

The expected competitive trends are helpful to identify the most sensitive suppliers to a change [22], [23]. In that sense, future trends in the market are required and each parameter must be predicted to simulate the increasing use of EWP in non-residential construction. Predictions of the concerned parameters are not available with enough information. So, it is essential to remind that a prediction remains highly uncertain. Such uncertainty will be part of our future work. Following, we present assumptions of the parameter's predictions concerning the building permits, the softwood lumber price and the share of NR building with wood structure. We assumed a constant evolution of the share of structural cost in the total building cost. This assumption implies that structural cost and building cost are linearly dependent.

To project the building permit, we assumed it to follow the existing population projection [21]. The observed strong correlation (R^2>0.8) between the total building permits and the population of Québec (figure 1) was the reason for this assumption.

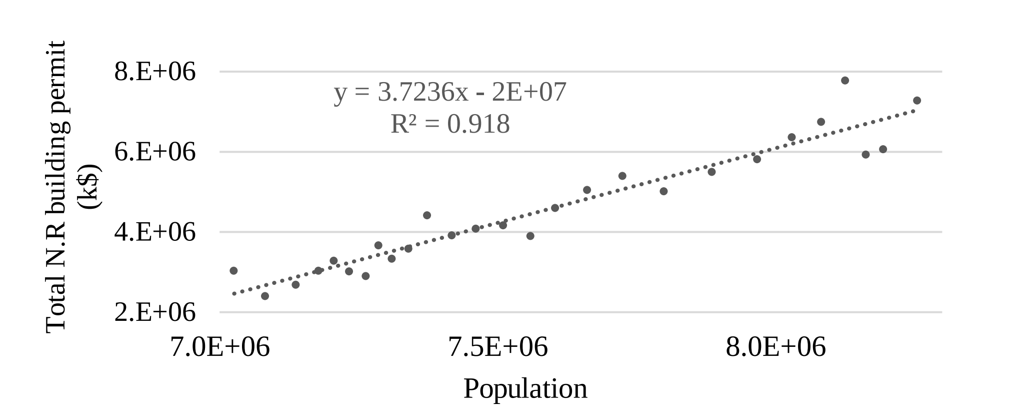

Figure 1. Correlation between building permits [17] and population [24] in Québec (1991-2017).

The following figures present the projections we made for the share of new NR buildings with wood structure (***WBs*** - figure 2) and the cubic meter price of the softwood lumber (linked to the ***WSp*** - figure 3). In the NR building structures, wood usage is an emerging market and no historical data are existing in the context of Québec. Therefore, we considered a prospective approach to model the increase of wood in the NR buildings. The projection of the potential share of building with wood structure is assumed to follow an S-shaped curve because the developments of EWP for building structure are not obvious linear process [25]. Indeed, when the first projects are successfully achieved and when the concerned public approves its technological breakthroughs, its development may follow a typical logistic S-growth [26].

Concerning the price projection, it follows the past trend of the average of the softwood lumber's prices (adapted from FEA - Forest Economic Advisors [27]). The minimum and maximum projection considered the historical minimum and maximum values which are projected following the trend of the average. This does not provide with precise figures but shows the price variability. As mentioned in subsection *2.1.,* the cubic meter price of the installed wood structure is considered in the modelling instead of the lumber cubic price. To do this, we applied a coefficient to represent the added value of the engineered wood product compared to lumber.

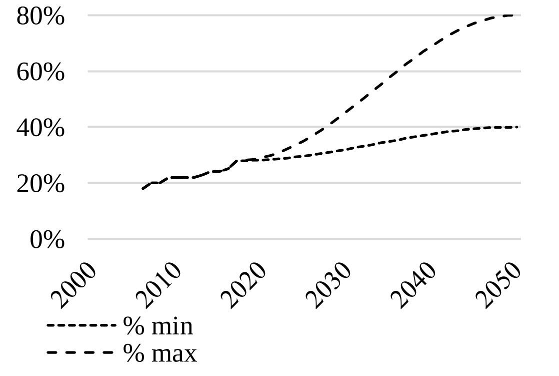

Figure 2. Projection of the potential share of the buildings with wood structure - WBs.

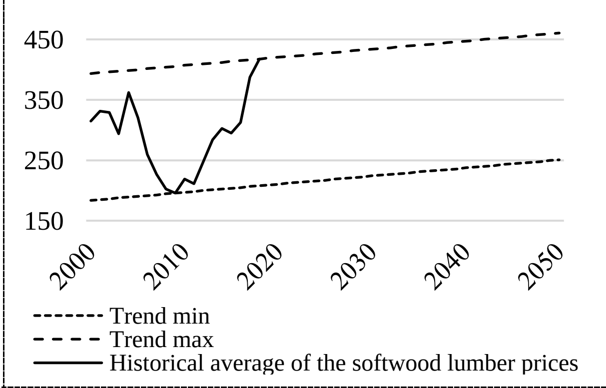

Figure 3. Projection of the softwood lumbers prices ($/m^3).

2.2.2. The wood supply chain
The modelling of the increasing wood demand drives the wood product flows throughout the supply chain (from the buildings to the forest). Therefore, to estimate the amount of wood resource, we investigated the wood supply chain. It is at the sawmill, when roundwood is processed into standard lumbers, that there is the higher loss of matter. Historical statistics gave the improvement trend of each sawmill yield for each output such as the lumbers, the wood barks, the chips and the sawdust per cubic meter of roundwood.

Projecting this improvement trend with a retrospective approach allows representing the sawmills' efforts to reduce co-products production (wood barks, chips, and sawdust) and increase efficiency. Indeed, those efforts include the use of thinner saws that reduce the cutting thickness, the use of optimized multi-saw slitting machines - straight sawing and curve sawing - and the recovery of parts during trimming to transform them into smaller parts [28]. We assumed the current trend will continue because changes are gradually as long as sawmills are improving their equipment. But this implies sawmills can invest thanks to the growing market. However, this reduction cannot be infinite. To do so, we constrained the reduction with an asymptotic limit of each yield according to the minimum values available in the statistics databases [29], except for the barks we supposed constant. Therefore, we projected the yields until their respective limit. But it is also important to notice that the number of lumbers and by-products must verify the material balance with roundwood as long as the yields are decreasing. So, if the yield of lumbers per roundwood reaches its limit before one of the co-products, the sum of the three co-products yields per roundwood cannot decrease anymore even if their respective assumed limits are not reached.

In order to evaluate the wood demand effect for NR building sector related to other sectors, we introduced the wood consumption of the other final uses in accordance with the material balance between the lumber imports, exports, and sawmill productions.

3. Results
The results relate to the estimated amount of wood products for the new NR building structures and the amount of roundwood which is required for this sector as well the others.

3.1. Wood in new NR structures
The following figure displays the two scenarios of the wood quantity for new NR building structures. We built these scenarios regarding the different uncertainties of the main parameters presented above.

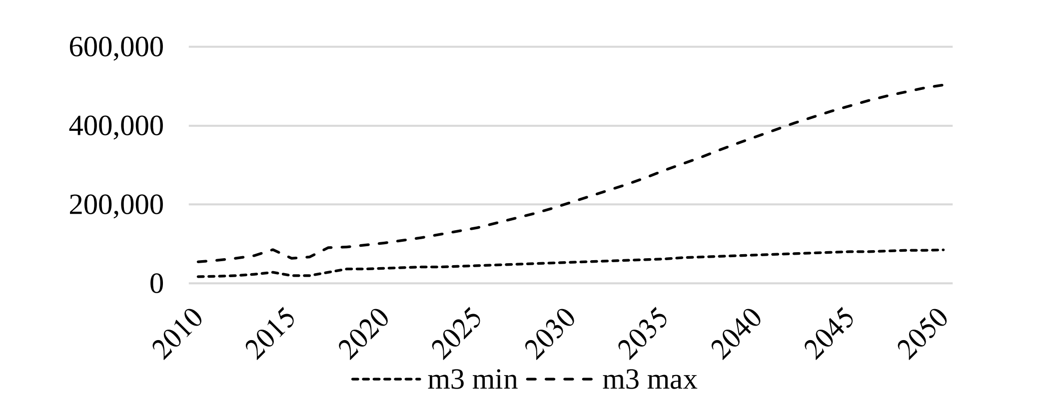

Figure 4. Estimation of wood products (m^3) in the structure of new NR buildings in Québec.

The minimum scenario follows an S-shaped curve, but the target of the ***WBs*** is so small that it seems to follow the trend. This scenario shows a negligible quantity because it also considers the maximum cubic meter price of installed wood in the structure. There is consistency in the sense that the more wood is expensive, the less it may be used. However, the price is not related to other endogenous parameters such as the availability of the resource.

3.2. Softwood roundwood harvesting

The importance of the additional softwood roundwood demand regarding the other domestic markets is illustrated in this section. The obtained results depict the additional demand for wood for NR building structures may be unconstrained by the resource availability if harvesting for other end-uses is constant. We also notice if the additional demand remains negligible and other end-use markets are constant, then the consequences of the decision may only occur in the investigated sector. This will imply to consider competition between structural material. Figure 5 shows the historical harvesting of softwood and resource availability in public and private forest in Québec [30] and the projections made. As shown in figure 5, even if the additional demand is negligible, considering the trend of other sectors will result in a constrained resource before reaching the expected time horizon.

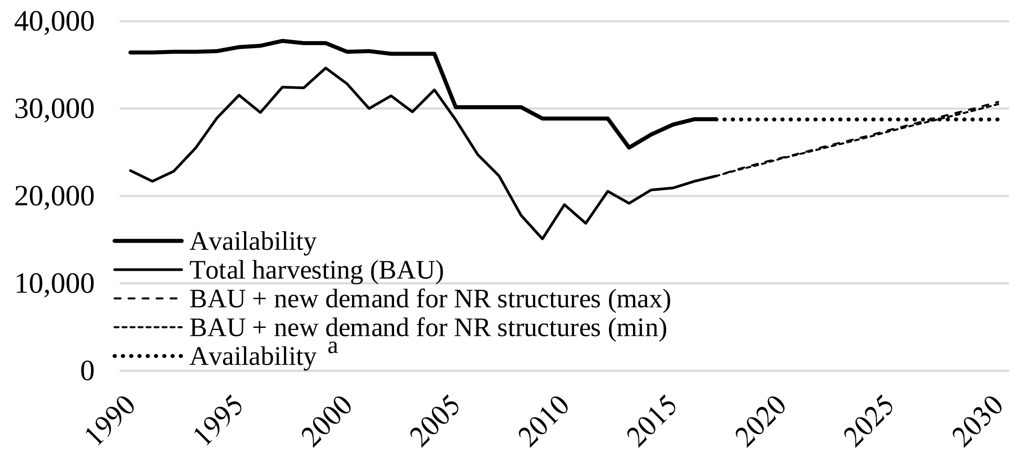

Figure 5. Total domestic softwood harvesting for NR building and others projected end-uses (‘000m^3). [a] Considering constant availability

The MFA allowed indicating the softwood lumber exportations [31] accounted for around 50% of the total harvesting in the 10 past years. This mainly drives the past harvesting trend implying that exportations may constrain the development of the NR wood products in term of resources availability. With the MFA in the wood supply chain, it is also possible to investigate the effects of additional sawmill by-products by assessing their potential demand for end-use markets (e.g. pulp, paper, cardboard, veneers, plywood, and panels, or Cogeneration and Energy Products).

4. Discussion

We presented a method to account for material in the emerging market of NR wood structure. Secondly, we investigated the dynamic wood flows in the supply chain to understand the effect of additional demand.

Regarding the account of material in the emerging market of NR wood structure, the parameter of the added value is specific to the wood buildings sector. Indeed, it allows considering the value which is added to wood during the EWP processing between the sawmill and the construction of the buildings. However, the lumber price is a dynamic and endogenous parameter and the added value is linearly dependent on it. By the end, the equation (1) respects the fact that, if the wood price is skyrocketing then it can deter timber harvesting. It results in an amount tending to zero. But there is a limitation here. The wood harvesting modelling does not consider the relationship between the resources price and its availability in the regional forest. In addition to that, the new buildings may not only include the structure

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but also the envelope which can possibly use wood. This additional demand for NR buildings is missing in this flow accounting. The quantity estimation is important to model representative additional harvesting regarding the potential of the emerging market to grow.

The results show how and when the limit in the resource availability can be reached depending on the assumption of all markets using the same resource. According to the assumptions, it does not appear relevant to look for consequences that will occur in the current supply chain because the wood quantity for NR building seems to remain negligible compared to others. One of the main sources of uncertainty in such studies concerns the evolution of the NR market related to others which use the same resources. It is an issue because both will contribute to reaching the limit.

Our research shows how MFA helps to identify EWP flows in the Québec non-residential buildings. This MFA provides a snapshot of the EWP use across years and considers trends. The estimation of wood quantity is related to the price, the population growth and the spending of the sector. It is important to underline that dynamic material flow analysis mainly consider 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 to estimate the material demand. Therefore, the presented methodology to estimate the quantity of wood should be compared to other methods using these parameters. Also, in the following work, system boundaries should be expended to understand the effects of EWP demand on the other structural materials as well as the effects of the stock accumulation on future discarded material.

To make the MFA less uncertain, we would need the share of the materials in the building archetypes and the distribution of those archetypes. But for an emerging market, dealing with a lack of data is obvious (non-existent or confidential). Also, as an emerging market, the price of the structure per cubic meter (WSp - $/m3) and the share of the structural cost among the building permit value (SCs - %) may be overestimated compared to a well-established future market. Concerning the wood products, we only considered the softwood sawnwoods, which are the raw products for structure products such as cross-laminated timber, glued-laminated timber or roof frame. As a consequence, the roundwood harvesting is overestimated because the sawnwood processing implies around 40% of material losses as barks, chips, and sawdust. If we considered a share for structural panels, such as oriented strand boards and laminated veneer lumbers, the processing yield would be less because all the roundwood (excepted the barks) is either destroyed as strands or laminated as laminated veneers. To overcome this bias, the share between the sawnwood products and other structural panels would help to disaggregate the cubic meter of the installed wood structure. This would imply one yield for the softwood sawnwoods and another one for the panels made of softwood and hardwood. As a consequence, the total and softwood harvesting would be less.

By tracking material flows of a sector, MFA supplies the CLCA modelling with a framework for several purposes. It identifies physical flows directly affected by a decision and models their trend. The dynamic MFA is a tool that brings insight into the evolution of a given economic sector thanks to a parameterized system-wide inventory of its flows. It supports the CLCA inventory modelling (i.e. the state of the market before and during the changes) and shows how the changes can be significant or constrained.

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