

# Challenging Mass-Based Exclusion Criteria: The Environmental Significance of Structural Connections in Timber Buildings

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In environmental impact assessments of buildings, the steel used in wooden structural connections, which are responsible for sustaining shear and tension stresses, is often overlooked yet could account for up to 13% of the total environmental impact over a building's lifecycle. This study assessed the importance of end-of-life management on the environmental impact of a hypothetical glued-laminated timber post-and-beam commercial building in Québec (Canada). The study used Life Cycle Assessment (LCA) and the SimaPro software, the EcoInvent database, and the TRACI impact assessment method. Assessing solely post-and-beam connections, LCAs were conducted at three scales, comparing 5 structural connections. Using heavy steel or aluminum structural connections leads to an impact of nearly 3% on global warming potential. It was found that the exclusion criteria used to simplify LCAs cannot be applied to structural connections. Multi-scale comparison of the connections—from individual component performance to their integration within the full building system—revealed significant variability in environmental outcomes. The study compared an improved end-of-life scenario with the current end-of-life scenario in Québec. The results showed a 7% reduction in the Climate Change impact category at the building scale. Early-stage design directions can affect end-of-life potentialities and practices with wood-building construction.

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## INTRODUCTION

The construction sector accounts for 36% of global final energy consumption and 39% of global energy-related greenhouse gas (GHG) emissions (Abergel *et al.* 2019). In Canada, this sector contributes approximately 17% of total GHG emissions (Statistics Canada 2025). Identifying low-carbon construction strategies in this sector could be part of the solution to climate change (World Green Building Council 2019; Rosa and MacDonald 2018). To assess the potential environmental impacts of a product, including buildings, throughout its life cycle, from production to end-of-life, a systemic approach called Life Cycle Assessment (LCA) can be used (ISO 14040 2006; ISO 14044 2006). Over time, this method has become essential for evaluating material and design choices (Guinée *et al.* 2011). In the context of buildings, LCA, when applied following a

standardized approach, is a crucial tool for assessing the environmental impacts of construction materials and guiding decisions toward more sustainable solutions.

Building LCAs have shown that the operational phase accounts for between 70% and 90% of the total environmental impacts and energy consumption over a building's life cycle (Ramesh *et al.* 2010). Policies have been implemented to reduce operational energy consumption, with recent programs such as Rénoclimat and Econologis in Québec in 2024 (Transition énergétique – Gouvernement du Québec 2025; Transition énergétique – Gouvernement du Québec 2023). Thanks to a 21% increase in building energy efficiency between 1990 and 2017 (Natural Resources Canada – Government of Canada 2019), the relative importance of the operational phase has decreased, leading to increased attention to embodied energy (Gustavsson and Joelsson 2010; Beccali *et al.* 2013), which includes impacts related to resource extraction, production, transportation, construction, replacement, deconstruction, recycling, or reuse (Mirabella *et al.* 2018). High-performance buildings now exhibit an embodied-to-operational emissions ratio of approximately 1:1, compared to 1:10 for traditional buildings (Röck *et al.* 2020). Reducing the embodied emissions of construction materials has thus become essential.

Wood-based products from sustainably managed forests are considered low-carbon materials (Rasmussen *et al.* 2020). Compared to standard materials such as reinforced concrete, brick (Hafner and Schäfer 2017; Žigart *et al.* 2018), or steel (Sandin *et al.* 2014), their impact is lower. A key strategy for reducing the carbon footprint is to use low-impact construction materials (Pomponi and Moncaster 2016). For example, in a conceptual office building (Helge Dokka *et al.* 2013), replacing a concrete and steel structure with a wooden structure offering similar technical performance reduced the weight by 30% and embodied carbon by 50%. Therefore, the structure's impact on the entire building is significant (Barnes Hofmeister *et al.* 2015). In the production of ready-to-use materials, wood consumes 60% to 80% less primary energy than concrete for the same structure, emitting CO<sub>2</sub> (Borjesson and Gustavsson 2000). In a study by Lippke *et al.* (2004), two houses were compared: one was modified to reduce wood use by 7% by replacing it with steel. This change resulted in a 26% increase in potential greenhouse gas emissions for the steel house compared to the wooden house. Consequently, using wood in construction can potentially reduce emissions in this highly polluting sector (Abergel *et al.* 2019).

In the province of Québec (Canada), political decisions have increased the share of four-stories or less non-residential buildings with a primary wooden structure from 15% in 2006 to 28% in 2016 (M. des Forêts, de la Faune, et des Parcs 2013). The provincial government has supported wood-friendly policies, such as the “Wood Integration Policy in Construction” (M. des Forêts, de la Faune, et des Parcs 2021). This transition is made possible by engineered wood products that meet the construction sector's needs. It is now possible to construct high-rise buildings using products such as glued-laminated timber (GLT), cross-laminated timber (CLT), or laminated veneer lumber (LVL). GLT offers a strength-to-weight ratio superior to steel or concrete (Moody and Hernandez 1997). This material enables structures such as the Richmond Olympic Oval in Canada, with spans over 100 meters. In Québec, the Telus Stadium spans 68.5 meters. These constructions require steel structural connections, which are often overlooked in building environmental impact assessments.

Hens *et al.* (2021) estimated that steel represents 4% of the total mass of a solid wood structure. This estimate is based on Strobel (2016), who calculated that steel accounts for 0.25% of the total volume of a solid wood structure. With embodied carbon coefficients (*i.e.* the measure of CO<sub>2</sub> emissions produced per unit of a material during its manufacturing

and sourcing process) of 0.512 for GLT and 1.55 for steel, the environmental impact of steel in wooden buildings is disproportionately high relative to its mass. Lukic *et al.* (2021) showed that among 13 studies examined, only 3 considered the impacts of structural connections. Their inclusion often depends on the availability of accurate inventories of material quantities.

Additionally, one of the three exclusion criteria in ISO 14044 (2006) allows for the exclusion of elements based on mass, with a suggested threshold of 1%, provided that the energy and environmental significance criteria are also satisfied. It often leads to the exclusion of structural connections, even though not all materials have the same environmental impact. Ignoring materials such as steel or aluminum solely based on their mass could result in inaccuracies. Structural connections play a crucial role in influencing the sizing of wooden structures and the building's overall impact.

Another aspect rarely addressed in studies is the end-of-life phase of buildings. Globally, only 7.2% of extracted resources are reintegrated into the economy after use (Circle Economy Foundation 2024), making this a major source of pollution. Building deconstruction is increasingly favored over demolition due to its economic and environmental benefits (Coelho and De Brito 2011). The state-of-the-art presented above shows that structural systems contribute to the overall impact, but structural connections are generally not included in calculations. Additionally, the importance of the end-of-life phase remains underestimated. Thoughtful choices in structural connections could prevent structural waste disposal from being the simplest solution.

To identify these impacts, the approach was divided into three modelling steps. First, Model 1 evaluates individual structural connections sized for identical loads, isolating the environmental impact of different connection technologies. Second, Model 2 expands the assessment to include the complete post-and-beam assembly, accounting for how connection design influences the sizing of adjacent timber members. Third, Model 3 integrates these assemblies into a complete building system to assess their relative significance at the building scale. The study calculates the impacts of each connection sized for a given load, considering that structural connections are designed to transfer shear and tension stresses between columns and beams. As a result, the environmental impacts associated with a connection are not limited to the steel connection itself but also include the surrounding structural wood required to ensure load transfer and structural performance.

Five different connection types were analyzed: Two-dimensional fitting (2DF), Three-dimensional fitting (3DF), Bridle joint (BDJ), Dovetail joint (DTJ), and 45° Screws (45S). Details of each connection type are provided in the Methodology section. An LCA of the systems, including structural connections and structures sized for the same load, was then conducted. Finally, these systems were integrated into a hypothetical building. This approach highlights the impact of structural connections, from their life cycle to their role in the building's life cycle assessment. The diversity of end-of-life scenarios, from complete incineration to full product reuse, underscores the importance of selecting an appropriate end-of-life cycle. The interest of this study lies in exploring the potential impact of structural connections in the building and the consequences of connection choices on end-of-life impacts. Two contrasting end-of-life scenarios will be evaluated to determine how minor changes can significantly reduce the impact of a wooden building, helping decision-makers design better, more sustainable buildings. Starting from the design phase, due to its direct and indirect impacts throughout the life cycle. This study aims to assess the significance of connection selection on the environmental impact of a

commercial building through an LCA of five structural connections in a GLT post-and-beam structure.

**METHODOLOGY**

**Scope and System Definition**

*Studied systems and functional unit*

A standardized Life Cycle Assessment (LCA) methodology at the international level was used to quantify environmental impacts, following the procedures described in the ISO 14040 (2006) and ISO 14044 (2006) standards. In the context of an LCA for buildings, ISO 21930 (2017) served as the reference for our case study.

The study’s objective was to assess the significance of connection selection on the environmental impact of a commercial building through an LCA of five structural connections in a GLT post-and-beam structure. The assessment considers the intrinsic impacts of a building model. According to the life cycle phases defined in ISO 21930 (2017) for evaluating the environmental performance of buildings, the production stages (A1-A3), as well as waste treatment (C3) and disposal (C4) during the end-of-life phase, are included. Figure 1 illustrates the system boundaries.

	Building life cycle																Potential benefits and loads
	Manufacturing stage			Construction stage		Use stage							End-of-life				
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	
	Raw material supply	Transport	Manufacturing	Transport	Construction - installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Recovery - Reuse - Recycling potential
<b>Initial embodied impacts</b>	X	X	X	X													
<b>Use stage impacts</b>																	
<b>End-of-life</b>															X	X	X

**Fig. 1.** System boundaries of this study, adapted from ISO (2011)

Life-cycle phases not included in the assessment are excluded from the system boundaries because they are considered functionally equivalent. Consequently, only these phases can be calculated by modifying the study’s result interpretation.

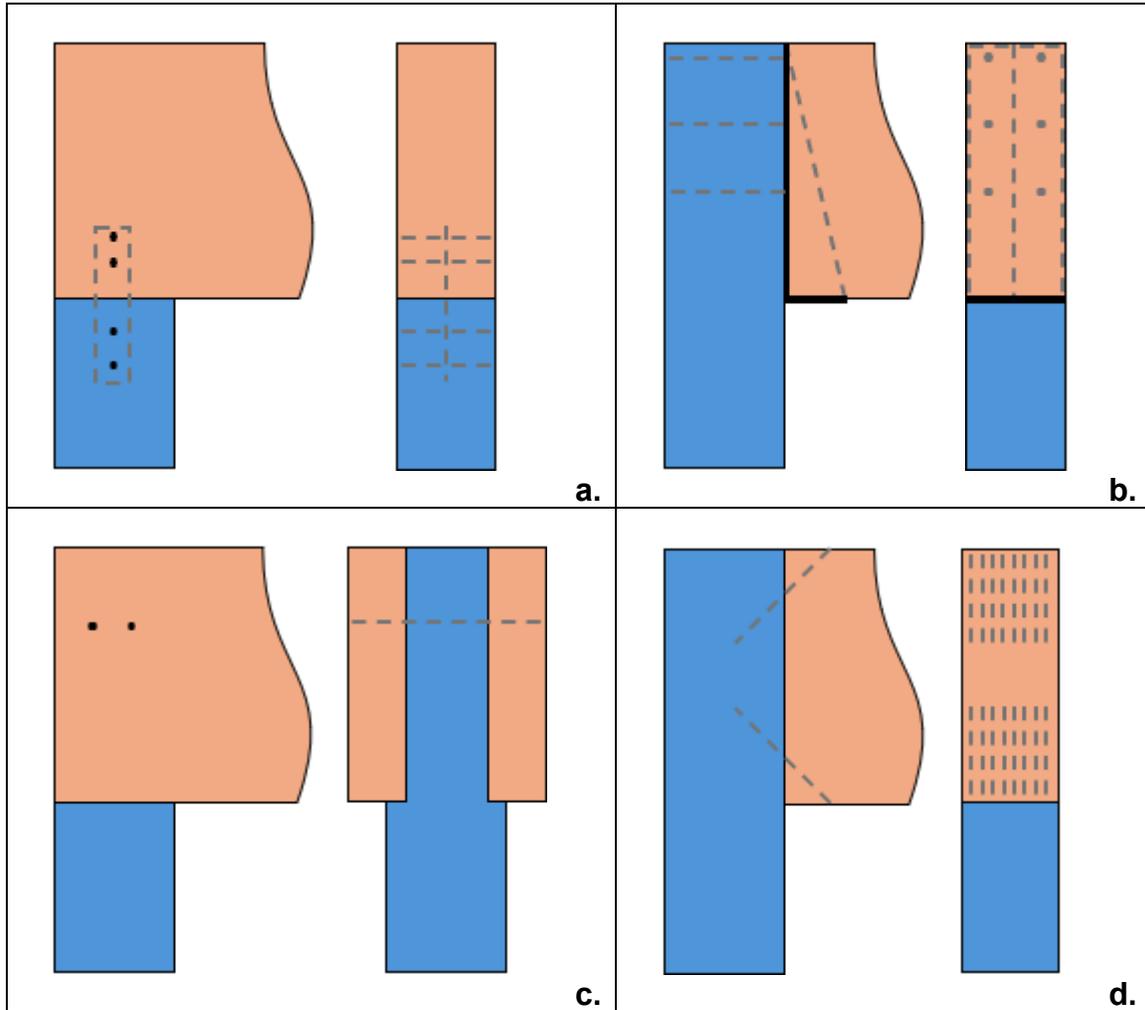
The systems under evaluation were assessed using a cradle-to-cradle Life Cycle Assessment (LCA) framework. This system boundary enables quantification of environmental benefits associated with closed-loop material flows. By reintegrating materials into the production cycle through strategies such as recycling and reuse, the cradle-to-cradle approach enables the accounting and visibility of avoided environmental impacts.

The studied system was the structural connection between a column and a beam in a post-and-beam construction system. It includes a column, a beam, and the connection that structurally links these components. The study focused on the connection responsible for sustaining shear and tension stresses. A comparison was made between five structural connections. There were selected as the most representative based on discussions with professionals, considering their diversity and use in GLT post-and-beam construction in the province of Québec, Canada. The selected structural connections are the Two-dimensional fitting (2DF), the Three-dimensional fitting (3DF), the Bridle joint (BDJ), the Dovetail joint (DTJ), and the 45° Screws (45S). The structural connections are illustrated in Fig. 2. The DTJ is not illustrated, as it corresponds to a proprietary commercial solution. Table 1 presents the mass of the materials constituting the structural connections and the associated post-and-beam system for a given functional unit (FU) of 100 kN, explained later.

The structural timber elements consist of GLT and beams. For the 2DF, the 3DF, the DTJ, and the 45S connections, posts measured 215 mm × 266 mm and beams measured 570 mm × 215 mm. For the BDJ connection, posts measured 265 mm × 266 mm, with two 570 mm × 130 mm beams. Figure 2 shows schematic representations of the connections from two different orientations. The two-dimensional fitting (2DF) comprises a steel plate positioned within the post web and secured by four bolts—two embedded in the post and two in the beam. The plate exhibited dimensions of 347.85 mm (length) × 77.05 mm (width) with a uniform thickness of 6.35 mm. Each bolt had a nominal diameter of 19.05 mm and an overall length of 215 mm. The three-dimensional fitting (3DF) was constructed using two orthogonally arranged steel plates and six bolts, all fastened exclusively to the post. The primary plate measured 215 mm × 570 mm, while the secondary plate measured 215 mm × 140 mm. Bolt dimensions remained consistent with those in the 2D bracket, with a diameter of 19.05 mm and a length of 215 mm. The Bridle joint (BDJ) consists of two 19.05 mm-diameter, 265 mm-long steel bolts that fasten the two beams on either side of the column. The Dovetail joint (DTJ) represents a prefabricated, proprietary connection offered commercially by structural hardware suppliers. The choice was made from the MTC Solutions catalog (2025). The joint used in this application is the MEGANT 430 × 150 model manufactured by MTC Solutions, featuring complex geometry. The 45° Screws (45S) include 16 inclined screws installed at 45°. Each screw has a length of 300 mm and a diameter of 8 mm. All steel components conformed to the ASTM A307 specification for steel fasteners. Only the post-and-beam connection was studied. This study did not examine other structural connections, such as beam-to-beam connections or bracing systems.

The functional unit (FU) is defined as transferring a 100 kN load in shear and tension to the support over an assumed building lifespan of 60 years, in accordance with LEED v4 certification (U.S. Green Building Council 2013). The reference flow was one connection per scenario. The LCA application across the models was incremental, all based on the same FU, applied from Model 1 onward.

The FU applies to Model 1, where structural connections are sized to withstand the load, and to Model 2, where the timber frames are sized to bear the load. Model 3 is an extension of Model 2, incorporating the materials of a complete building, and FUs correspond to the building's broader functions (e.g., fire performance, thermal/acoustical insulation). The complete description of the FUs can be found in Hosseini *et al.* (2023).



**Fig. 2.** Illustration of four of the five structural connections studied, each shown with its corresponding post-and-beam assembly: (a.) Two-dimensional fitting, (b.) Three-dimensional fitting, (c.) Bridle joint, and (d.) 45° screws. Detailed dimensions are provided beneath the figure.

**Table 1.** Structural Connections and Associated Posts-and-Beams Mass (in kg), Dimensioned for 100 kN Shear and Tension Stresses

Structural connections	2DF	3DF	BDJ	DTJ	45S
Steel	3.1	12.3	0.2	8.3	0.7
Aluminum	0	0	0	3.6	0
Wood	675.4	675.4	818.7	675.4	675.4

### Building Model Description

The hypothetical building model examined in this study is based on the research by Hosseini *et al.* (2023). It is a commercial timber building with dimensions of 12.72 meters

by 6.60 meters. The total area of 6,198 m<sup>2</sup> is spread over six stories, including a basement. The construction system is a post-and-beam system made of glued-laminated black spruce (*Picea mariana* (Mill.) B.S.P.) from Québec, with cross-laminated timber (CLT) floors. The building was designed with a concrete core and CLT shear walls, and it contains 315 post-beams, each with two connections (630 in total). Structural calculations were performed for Québec (Canada) in compliance with the National Building Code of Canada (N.R.C. of Canada A.C. on the N.B. Code 2020). Table 2 presents the material quantities provided by the architect. Quantities are expressed as a percentage of the total building mass. These values account for all five connections studied and report only the minimum and maximum values observed among them. Only the masses of aluminum, steel, and GLT vary across the models, as these materials constitute the focus of the study and are the only ones whose quantities differ between the connection configurations. The percentage variations observed for the remaining materials result solely from changes in their relative proportions within the overall material composition, since their absolute quantities remain constant across all scenarios.

**Table 2.** Mass of the Building Component Considered in This Study. The prefix 'Studied' identifies the specific connection and timber components studied in this study. Percentages are calculated independently for each of the five connection solutions, resulting in MIN totals <100% and MAX totals >100%

Materials	Min (%)	Max (%)
Studied aluminum	0.00	0.09
Studied steel	0.00	0.13
Studied GLT	7.46	8.89
Bitumen seal	0.24	0.25
Clay brick	10.45	10.64
CLT	10.24	10.42
Concrete	54.32	55.30
Polystyrene extruded	0.14	0.14
Glass	0.21	0.22
Glass wool mat	1.58	1.60
Gypsum fiberboard	3.34	3.40
Gypsum plasterboard	5.53	5.63
Plywood	0.04	0.04
Stainless steel	0.57	0.58
Steel	4.12	4.19
Woodstud	0.11	0.11

#### *LCA models – From connections to building*

The LCA modeling was conducted on three models, each at a different scale. Model 1 corresponds to the study of structural connections alone. These were dimensioned to meet the building's structural requirements in Model 3. Model 2 encompasses the structural connection mechanisms integrated within a post-and-beam framework, specifically comprising timber structural members and metal fasteners. In contrast, Model 3 provides a holistic depiction of the edifice, extending beyond Model 2 by incorporating vertical enclosure systems (*i.e.*, wall assemblies), roofing structures, and subsurface foundation elements. It is important to note that in Model 3, the building, its materials, and their quantities are identical across all connection types. The analysis of Model 3 is conducted to assess and understand the impact of each solution at the building scale. Analyses were

performed for each model across all connection types, allowing a comparative evaluation of results at each scale.

## Life Cycle Assessment Framework

### *Life cycle inventory and impact assessment*

The LCAs were conducted using SimaPro 9.0. To ensure the transparency of the datasets used and the representativeness of the results, the generic database EcoInvent v3.5 (Wernet *et al.* 2016) was selected, incorporating average environmental datasets for construction materials. The chosen system model was “Allocation, cut-off by classification – unit.” For this project, processes from the Québec region were used. European processes were employed when unavailable, adapted to Québec’s energy mix. The selected impact assessment method was TRACI 2.1 (Bare 2011), which aligns with the project’s geographic scope. During the modeling phase, the impact categories evaluated included Ozone Depletion, Global Warming Potential, Smog, Acidification, Eutrophication, Carcinogenic and Non-carcinogenic Toxicity, Respiratory Effects, Ecotoxicity, and Fossil Fuel Depletion.

A commercial timber construction expertise center sized the studied structural connections according to the project requirements. The load-bearing capacity of the structural connections was determined in accordance with manufacturers’ guidelines or recommendations from expertise centers.

Critical reviews were conducted in accordance with ISO 14040 (2006) and ISO 14044 (2006) to verify the robustness of the results through sensitivity analyses (presented in the Results section).

### *Study assumptions*

The assumptions made in this study are detailed per life cycle phase as follows.

For the production phase (A1-A3), for Models 1 and 2, the life cycle inventory data for the production phase includes raw material extraction (A1), transportation of production materials to the manufacturer (A2), and material manufacturing (A3). The structural connections are made of steel and aluminum, recycled according to the European standard rate and sourced from Eastern Europe. The final processing, depending on the manufacturer, occurs either in southern Germany or central Austria. The structural connections are transported by truck, then by ship, and again by truck to the retailer. European products were selected based on common practices observed in Québec’s construction sector. North American alternatives exist and could be considered in future studies. For the columns and beams, the wood is sourced from Québec’s forests, processed in the province’s north, and then transported to the construction site by truck. Québec’s energy mix consists of 99% renewable energy (Canada Energy Regulator 2017). For Model 3, the assumptions from Models 1 and 2 are maintained for the materials used in Models 1 and 2. The selection of processes in EcoInvent emphasized consistency between the system studied and the geographic scope of the data, prioritizing Québec-specific entries (CA-QC) due to the province’s predominantly renewable energy mix. When CA-QC data were unavailable, European datasets (RER) were used as proxies, while broader Canadian datasets were excluded due to their misalignment. If neither CA-QC nor RER were applicable, global data (GLO) were adopted. A full list of selected processes appears in the Appendix (Table S1.).

For End-of-life phase (C2-C4), construction waste from the building’s demolition must be transported from the demolition site to a sorting center or collection point, where

it is then directed for recycling, reuse, incineration, energy recovery, or landfill disposal. End-of-life transportation was excluded from the study's scope, as it is assumed to be equivalent across all solutions to provide a global rather than a local response.

## End-of-Life Scenarios Development

### *End-of-life scenarios and assumptions*

Two end-of-life scenarios were proposed to assess the impact of the structural connections. The first scenario is the baseline scenario, corresponding to the current end-of-life scenario for materials in Québec, based on data from Recyc-Québec (Recyc-Québec 2021) (Table 3). Table 3 presents end-of-life strategies as reported in the source. The data from this source are not specific to the construction sector. The end-of-life strategy in the “wood” row is applied to CLT, GLT, and wood stud components. In the Results section, it is referred to as the QUEB scenario. The second scenario is an optimal scenario named OPTI. The OPTI scenario was developed as a technically achievable best-case scenario, representing the maximum recovery potential under current technological capabilities and best practices in Design for Disassembly (DfD). This scenario assumes a mature reverse logistics infrastructure and systematic application of DfD principles—conditions not yet standard practice but technically viable. The gap between OPTI and QUEB therefore represents the improvement potential through policy intervention, market development, and design optimization rather than technological breakthroughs. For instance, achieved recycling rates of 100% for standardized steel connections reflect proven industrial capabilities (Broadbent 2016) rather than aspirational targets.

**Table 3.** End-of-Life Strategy Rates QUEB Scenario

Materials	Landfilling	Incineration	Recycling	Reusing
Concrete	69%	0%	31%	0%
Brick	69%	0%	31%	0%
Insulation	100%	0%	0%	0%
Steel	70%	0%	30%	0%
Gypsum	99%	0%	1%	0%
Bitumen	72%	27%	1%	0%
Wood	63%	27%	10%	0%
Glass	50%	0%	50%	0%
Aluminum	70%	0%	30%	0%

Table 4 illustrates the maximum end-of-life rates defined in consultation with structural engineers. Regarding the structural connections, non-standardized elements, such as 3DF and 2DF, are recycled. It was assumed that their specificity hinders reuse. The standardized DTJ connection is reused. Although the 45S is standardized, it is recycled. Observations have shown that screws are often in poor condition after a single use and that operators have difficulty removing them from the wood due to thread damage during construction. Screws are present in both the 45S and DTJ. The standardized BDJ connection is reused. Threaded rods found in 2DF, 3DF, BDJ, and DTJ are also reused.

It was decided not to reuse beam sections subjected to high stress, nor sections that have been drilled or screwed. Thus, only intact beam sections are reused, while damaged sections are systematically recycled. For connections with screws, damaged wood sections are first shredded, then magnets are used to extract the screws before the wood is recycled. In the absence of screws, the damaged section is directly recycled. In all cases, the wood

is recycled into composite panels (particleboards and insulation fiberboards), a well-established industry in Canada.

**Table 4.** End-of-Life Strategy Rates OPTI Scenario

Materials	EoL Strategy	2DF	3DF	BDJ	DTJ	45S
GLT	Landfilling	19 %	19 %	19 %	19 %	19 %
	Incineration	12 %	9 %	13 %	13 %	12 %
	Recycling	3 %	3 %	3 %	3 %	3 %
	Reusing	66 %	69 %	65 %	66 %	66 %
Connection Steel	Landfilling	0 %	0 %	0 %	0 %	0 %
	Incineration	0 %	0 %	0 %	0 %	0 %
	Recycling	41 %	77 %	0 %	100 %	100 %
	Reusing	59 %	23 %	100 %	0 %	0 %
Aluminum	Landfilling	/	/	/	0 %	/
	Incineration	/	/	/	0 %	/
	Recycling	/	/	/	100 %	/
	Reusing	/	/	/	0 %	/

Note: 2DF, Two-dimensional fitting; 3DF, Three-dimensional fitting; BDJ, Bridle joint; DJT, Dovetail joint; 45S, 45° Screws

It remains challenging to rely on standards such as CSA S16: Design and construction of steel structures (CSA Group 2024), which provides only general guidelines for assessing and reusing steel. In contrast, Europe's Eurocode 3 (or NF EN 1993-1-1) (ISO 2013) offers much more precise guidance. However, it was not applied in this study. The objective is to demonstrate the potential for steel reuse. Therefore, steel is reused whenever technically feasible.

In the LCAs presented in the Results section, the term QUEB scenario is used when it applies to all materials. The term OPTI scenario indicates that the OPTI scenario is applied to the studied components, specifically the structural connections and the associated post-and-beam systems. It corresponds to 100% of Model 1 and 100% of Model 2. At the building scale (Model 3), this scope corresponds to the components identified with the prefix 'Studied' in Table 2, representing approximately 7% to 8% of the total building mass.

Biogenic carbon was included in this assessment to account for the carbon sequestration potential of timber components. This inclusion is particularly relevant for DfD, as extending the service life of timber elements effectively prolongs the carbon storage period and delays the release of CO<sub>2</sub> into the atmosphere. This approach aligns with circular economy principles by highlighting the benefit of retaining bio-based materials within the technosphere (Gustavsson *et al.* 2006).

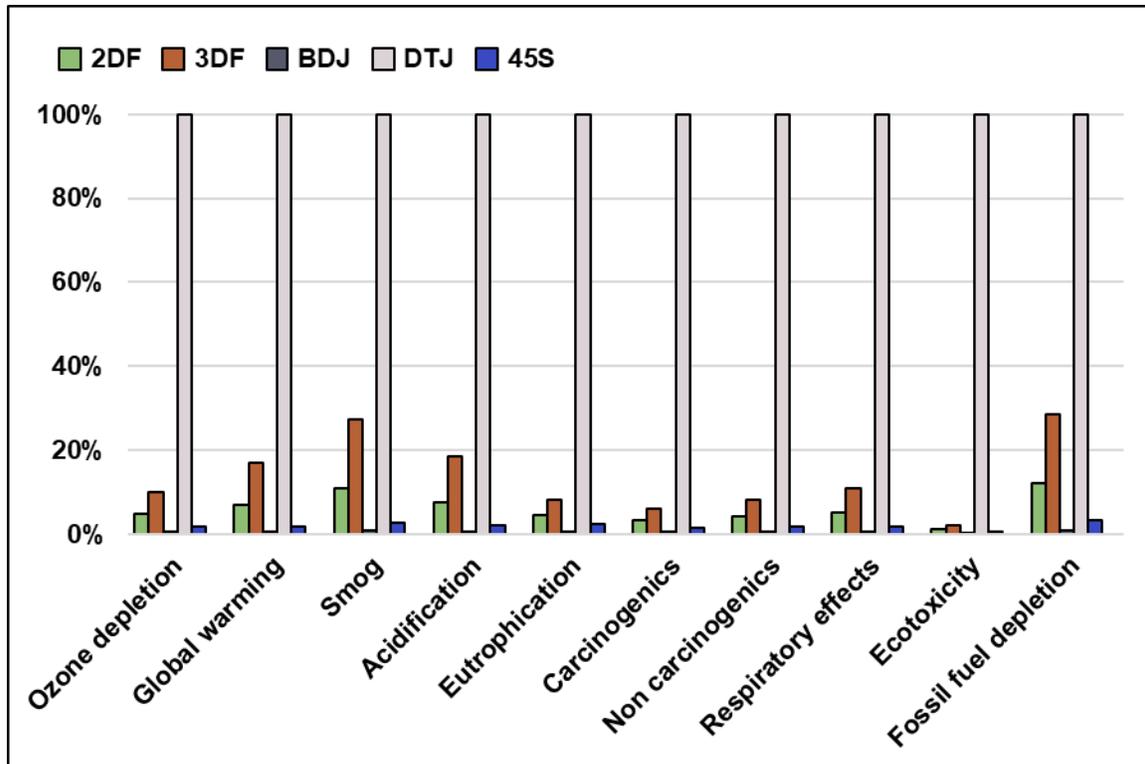
## RESULTS AND DISCUSSION

### Model 1: Structural Connections

The Life Cycle Assessment (LCA) results for structural connections – as shown in Fig. 3 – were normalized to compare relative environmental impacts across diverse categories, each with different units. The connection with the highest life-cycle impact for each impact category was set as the benchmark (100%), and the others were evaluated relative to it. These results include both the production and end-of-life phases to account

for potential environmental credits associated with actions such as recycling or reuse. Acronyms for each connection type analyzed in the results section were described in Fig. 2. Note that from Figs. 3 to 5, the presentation of data follows the same principles.

The detailed results of each life cycle phase and each material are provided in Appendix Table S2. Negative values can be observed in impact categories, which corresponds to the C and D modules shown in Fig. 1. This results from the methodological choice to avoid allocating impacts to the production of raw materials when the materials are recycled or reused. Since there is no scientific consensus for this aspect, this modelling assumption was adopted in accordance with the present goal and scope definition.



**Fig. 3.** Model 1 LCA results with TRACI 2.1 and QUEB scenario – 2DF: Two-dimensional fitting, 3DF: Three-dimensional fitting, BDJ: Bridle-joint, DTJ: Dovetail-joint, 45S: 45° screws

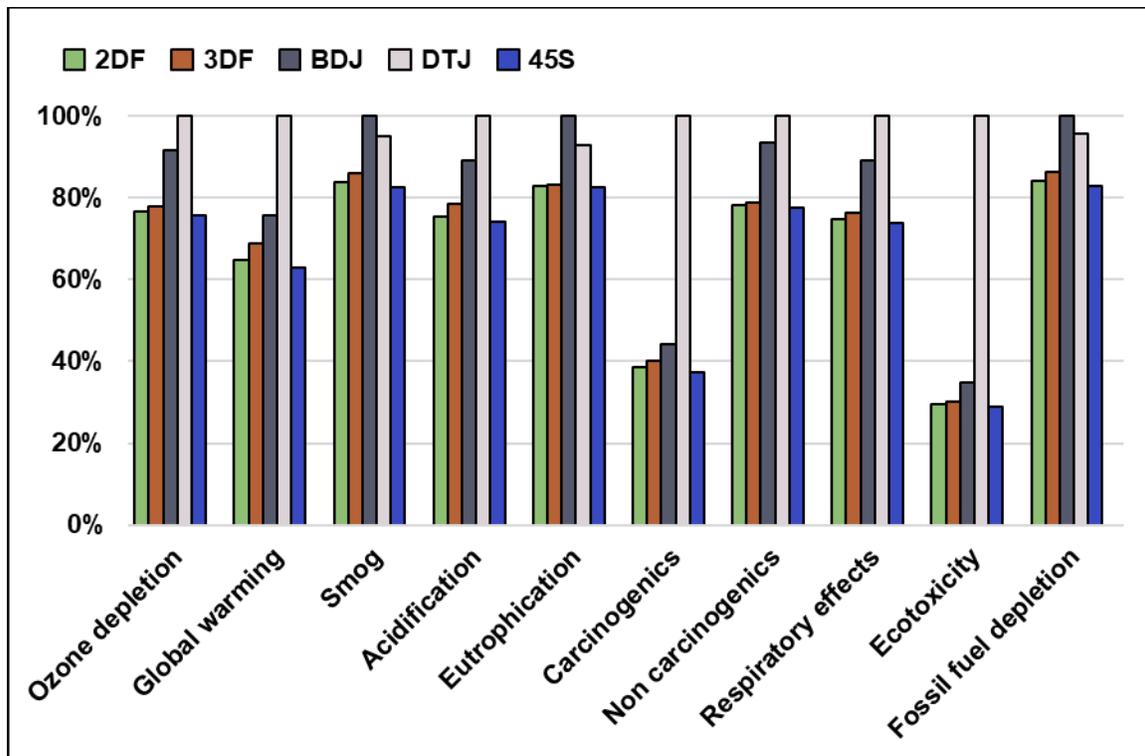
The results show that the DTJ has the highest relative impact in all categories. The BDJ has the lowest relative impact in all categories. The 2DF has a lower relative impact than the 3DF in all categories. The 45S has a lower relative impact than the 2DF and 3DF in all categories. From most to least impactful, this ranking corresponds to the mass rankings observed in Table 1. The impact of the structural connections is linked to their mass. At this scale of study, mass is the only differentiating factor. However, the comparison also reveals a significant difference between the DTJ and the four other structural connections. This is due to the composition of this connection, which consists of approximately 70% aluminum. Aluminum is responsible for 84% of the Global Warming Potential impacts (see Table S1.). Aluminum is about 5 times more carbon-emitting than steel (Norgate *et al.* 2007).

At the scale of individual structural connections, environmental impacts are dominated by material properties and masses. At this scale, it can be concluded that the choice of connection is significant. The difference between structural connections is

substantial enough to induce variations in Model 1. The results suggest that BDJ is the best solution. However, assessing the impacts of structural connections solely based on connection-level impacts does not determine their relative importance within a building.

## Model 2: Assembly Systems

Figure 4 presents the LCA results for Model 2. This model includes the connection and the associated post-and-beam system. The corresponding values are reported in Table S3.



**Fig. 4.** Model 2 LCA results with TRACI 2.1 and QUEB scenario – 2DF: Two-dimensional fitting, 3DF: Three-dimensional fitting, BDJ: Bridle-joint, DTJ: Dovetail-joint, 45S: 45° screws

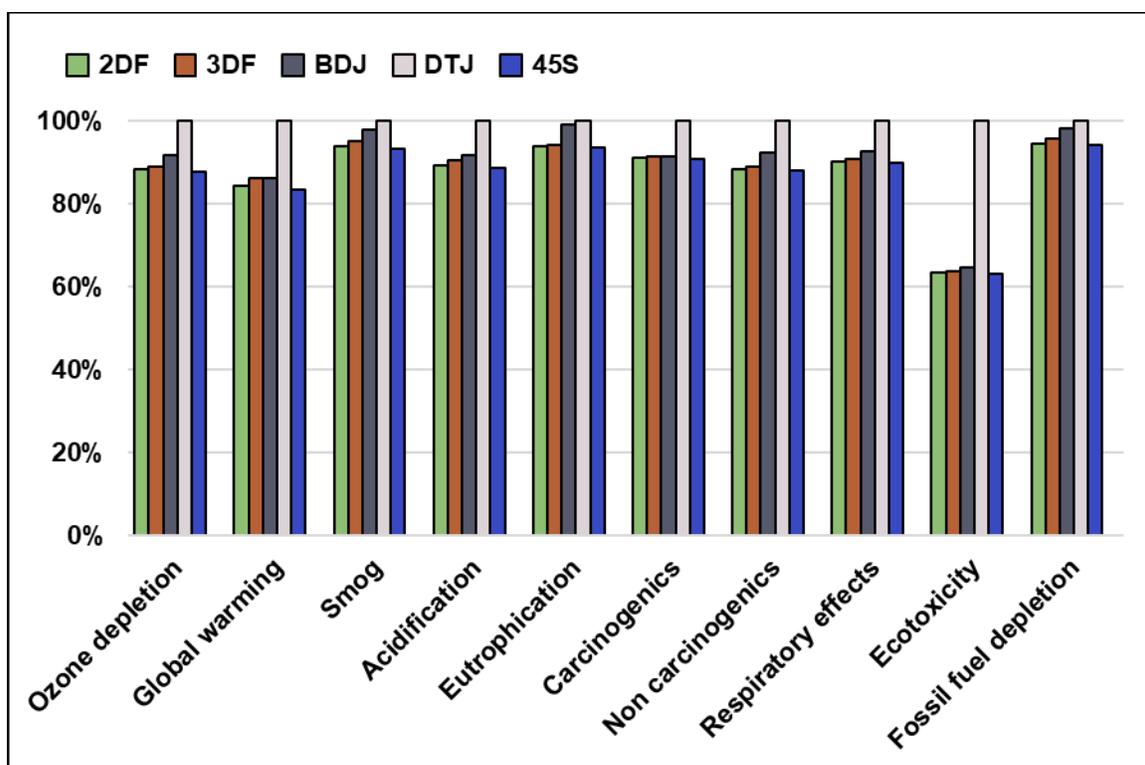
The DTJ has the highest relative impact in 7 out of 10 impact categories, while the BDJ has the highest impact in 3 out of 10 categories. In Model 1, the DTJ was the most impactful solution in all impact categories, and the BDJ was among the least impactful. The transition from Model 1 to Model 2 changes this conclusion. Incorporating the post-and-beam system into the LCA calculations alters the conclusions. Initially perceived as the best solution, the BDJ no longer seems relevant. This change is explained by the increase in the amount of wood required for this specific connection system. All post-and-beam systems were sized identically, except BDJ. As presented in the Methods section, Table 1 shows that the BDJ is the heaviest system. This assembly technique requires the oversizing of the column and beams. This traditional wooden joint relies on a larger wood section for a smaller connection, resulting in a 25% increase in wood use, particularly evident in the eutrophication category. Eutrophication is related to elements such as nitrogen. This potential impact is mostly due to forest management of wood products and therefore depends on available data and the model implemented in the environmental database.

The 45S, 2DF, and 3DF differences are too small (often less than 5%) to identify a more advantageous solution. All three solutions become most relevant after the scale change (*i.e.*, considering the entire post and beam system rather than just the connection).

This demonstrates that the connection design influences the structure's impacts. Mass remains an important factor, but the materials, aluminum in this case, is the most decisive factor. This material particularly influences Ecotoxicity and Carcinogenics due to its chemical production processes.

### Model 3: The Building

In Model 3, the objective is to determine whether the performance differences between the solutions—observed in Models 1 and 2—remain significant at the building scale. Figure 5 compares five buildings, each integrating one of the five structural connection types.



**Fig. 5.** Model 3 LCA results with TRACI 2.1 and QUEB scenario – 2DF: Two-dimensional fitting, 3DF: Three-dimensional fitting, BDJ: Bridle-joint, DTJ: Dovetail-joint, 45S: 45° screws

The different structural connections are considered only for the post-and-beam assembly. The rest of the building's timber structure is identical across all cases. Three out of ten impact categories show differences below 5% between structural connections, and five out of ten categories show differences below 10%. From a methodological standpoint, such margins fall within the inherent uncertainty range of background Life Cycle Inventory (LCI) data and Impact Assessment (LCIA) methods (Heijungs and Huijbregts 2004). Given that generic datasets (Ecoinvent) were used rather than specific Environmental Product Declarations (EPDs), these slight deviations are insufficient to establish a definitive environmental ranking at the building scale. The environmental 'signal' of the specific connection choice is effectively diluted by the total building mass and the cumulative

uncertainty of hundreds of material processes. In Models 1 and 2, the choice of connection produced clear distinctions in environmental impacts. In Model 3, these differences are no longer significant, and the BDJ is no longer impactful as in Model 2. It is explained by the number of structural connections and post-and-beam systems involved (see Methodology). This leads to a loss of distinction between the solutions. A general difference can nevertheless be observed between the DTJ and the other solutions. The impact category “Ecotoxicity” remains sensitive to aluminum, with the DTJ continuing to be the most impactful solution in this category.

The detailed calculations (see Table S4.) present a grouping of materials. The “other” materials correspond to those not included in Model 2. These materials appear in the last 13 rows of Table 4 and account for 90% to 92% of the total building mass (as shown in Table 4). Their end-of-life phase accounts for 55% to 97% of impacts across all connections and categories.

The scaling effect reduces the significance of structural connections. At the scale of Models 1 and 2, the influence of the structural connections is noticeable and substantial. At the scale of Model 3, however, it is no longer possible to draw environmental conclusions about the superiority of one connection over another.

## Propagation of Impacts

### *Relative mass and impact analysis*

A critical methodological question in life cycle assessment concerns the application of exclusion thresholds. ISO 14044 allows the exclusion of materials or components that represent less than 1% of the total mass or energy. However, the relevance of mass-based criteria for materials with high environmental intensity—such as metals in timber structures—remains debatable.

Table 5 addresses this issue by comparing the relative mass and Global Warming Potential (GWP) contributions of the 3DF connection across the three models under the QUEB scenario. For each model, the figure juxtaposes material masses (left column) with their associated impacts (right column), making visible the discrepancy between physical weight and environmental weight. At the connection scale (Model 1), steel accounts for 100% of both mass and impacts, with an absolute impact of 40.5 kg CO<sub>2</sub>-eq under the QUEB scenario.

**Table 5.** Relative Comparison of Masses and Global Warming Potential (GWP) Impacts of the 3DF Connection under the QUEB Scenario, Assessed Using TRACI 2.1

	Model 1		Model 2		Model 3	
	Mass	Impacts	Mass	Impacts	Mass	Impacts
Connection's steel	100%	100%	3.5%	9.4%	0.3%	3.4%
Structure's wood			96.5%	90.6%	7.3%	16.3%
Other materials					92.4%	80.3%

In Model 2, although wood accounts for 96.5% of the total mass, it accounts for only 90.6% of the impacts. Conversely, steel—representing only 3.5% of the mass—contributes 9.4% of impacts. It corresponds to a mass-to-impact ratio that is nearly three times higher for steel than for wood ( $9.4\% / 3.5\% = 2.69$  vs.  $90.6\% / 96.5\% = 0.94$ ), reflecting steel's inherently higher environmental intensity. In Model 3, these mass-to-

impact ratios shift ( $3.4\% / 0.3\% = 11.33$  for steel vs.  $16.3\% / 7.3\% = 2.23$  for wood). This evolution is explained by the introduction of “other materials” at the building scale. This category includes all materials not specifically studied in detail (Table 4), as the primary focus of the study lies on connections. It represents 92.4% of the building’s mass but only 80.3% of its impacts due to their end-of-life (explained in Results). Most of these materials are landfilled in the QUEB scenario. TRACI 2.1 characterizes this process as having low emissions. Therefore, their end-of-life impact is small compared to their total mass.

When moving from Model 2 to Model 3, the relative contributions of wood and steel appear to shift visually, but their fundamental relationship remains unchanged. Comparing the masses of steel and wood between Model 2 and Model 3 reveals a slight difference (a factor of 27 in Model 2 and 24 in Model 3). The steel/wood impact ratio (9.6 vs. 4.8) reflects the ratio of 2 applied to the quantity in Model 3 (see Methodology).

At the building scale (Model 3), Table 5 shows that the steel used in the 3DF connections accounts for 3.4% of the total GWP of the building, while representing only 0.3% of its mass. When considered together with the associated structural wood, the connection system (steel connections and adjacent timber elements) represents a combined 19.7% of the building’s GWP (3.4% for steel and 16.3% for wood). This indicates that the impacts attributed to connection-related components extend well beyond the connection itself and propagate to a substantial share of the building.

This finding confirms that structural connections—despite their modest mass—represent a significant leverage point for environmental optimization and cannot legitimately be excluded from detailed LCA studies solely based on low mass. This justifies the present study’s focus on connection-level scenarios and motivates the development of the optimized end-of-life scenario (OPTI) analyzed below.

#### *QUEB and OPTI scenario comparison*

Having established the environmental significance of structural connections, the following analysis evaluates the effectiveness of an optimized end-of-life scenario (OPTI) in reducing their impacts. Table 6 illustrates the propagation of these impact reductions from the component scale (Model 1) to the building scale (Model 3) by comparing the baseline QUEB scenario with the OPTI scenario for the 3DF connection.

**Table 6.** Comparison of the Relative Impact Propagation in the Global Warming Potential (GWP) Category for the 3-Dimensional Fitting Connection under QUEB and OPTI Scenarios, Using the TRACI 2.1 Method

	Global Warming Potential (kg CO <sub>2</sub> eq)					
	Model 1		Model 2		Model 3	
	QUEB	OPTI	QUEB	OPTI	QUEB	OPTI
Connection's steel	40.5	28.5	40.5	28.5	25499.0	17955.0
Structure's wood			389.1	235.0	122567.3	74029.4
Other materials					601968.1	601968.1

In Model 1, the OPTI scenario achieves a reduction of nearly 30% in impacts (from 40.5 to 28.5 kg CO<sub>2</sub>-eq), demonstrating the optimization potential at the connection scale through improved steel recycling pathways.

In Model 2, impacts are dominated by wood, representing 82.8% under QUEB and 80.5% under OPTI. Interestingly, the relative reduction is greater for wood than for steel: the OPTI scenario reduces wood impacts by 39.6% (from 389.1 to 235.0 kg CO<sub>2</sub>-eq), compared with 29.6% for steel. This reflects the significant influence of end-of-life options for timber, where alternatives to open burning—such as energy recovery or cascading reuse—greatly reduce GWP burdens.

In Model 3, the “other materials” category appears. The OPTI scenario is not applied to these materials, which explains their stable impacts at 601,968 kg CO<sub>2</sub>-eq. Consequently, the relative effectiveness of the OPTI scenario diminishes at the building scale while remaining significant in absolute terms. At this scale, the OPTI scenario yields a reduction of approximately 7.5% in the GWP category, corresponding to an emission reduction of about 56,000 kg CO<sub>2</sub>-eq—a non-negligible contribution given that it concerns only the structural connections and their associated timber components.

It is important to distinguish the direct contribution of the connections from their cascading effect on timber recovery. When isolating only the connection materials (steel and aluminum) within the OPTI scenario, the GWP reduction drops to approximately 1%. The difference between 1% (connections alone) and 7.5% (connections + enabled timber recovery) quantifies the indirect environmental value of connection choices. While representing less than 0.5% of building mass, connections determine the circularity potential of 7 to 8% of structural mass. This leverage effect underscores that the primary environmental significance of structural connections lies not in their direct material impacts but in their role as gatekeepers to timber reuse.

Additional calculations were performed for the other structural connections studied (results not shown). Impact reductions at the building scale under the OPTI scenario range from 6.28% to 7.32%, with the BDJ achieving a notably higher reduction of 15.64%. Since the OPTI scenario applies only to the connections and their associated timber elements, it is logical that the most environmentally intensive solutions—those involving larger quantities of steel or wood—achieve the largest absolute reductions. These findings reinforce the conclusion that optimization efforts in timber buildings should prioritize not only material selection but also end-of-life pathway planning, particularly for timber treatment and steel recycling infrastructure.

## Implications for Practice

The comparison between QUEB and OPTI scenarios highlights that the environmental benefits of timber buildings are heavily dependent on the ability to recover materials. To transition from theoretical OPTI results to practice, specific design strategies for fasteners and standardization must be addressed.

Screws, whether used as structural connections or as part of them, present significant challenges for circularity. Although they are lightweight and showed lower environmental impacts in the production phase of this study, their durability limits reuse potential. Screws are frequently single-use components due to head stripping or bending during extraction. Furthermore, they often become embedded in beams or columns, damaging the timber matrix and reducing the structural element’s reuse potential. This physical damage necessitates the conservative reuse rates applied in the OPTI scenario (Table 3), where timber sections with embedded fasteners were assumed to be recycled rather than reused. While using oversized screws could improve durability, prioritizing connections that avoid embedding metal into wood is preferable for long-term circularity.

The study revealed that while the specific connection type has a limited impact on the Model 3 GWP score, it is decisive for the end-of-life scenario. A major obstacle to connection reuse is the uniqueness of current building designs, which result in structural elements being customized for each project. While standardizing entire structural grids may limit architectural freedom, standardizing the connection interface offers a pragmatic compromise. For instance, the mortise-and-tenon joinery analyzed in this study relies on standardized threaded rods. The complexity lies in the timber notches (joint housings); if these interfaces were standardized across the industry, beams and columns could be more easily interchanged between buildings. Furthermore, these notches are machined in workshops, simplifying on-site assembly and subsequent disassembly.

The gap between the potential reuse (OPTI) and current practices (QUEB) is largely logistical. Since reuse remains an uncommon practice, predicting storage duration is difficult, though it is expected to be significant. To mitigate the environmental burden of long-term storage, which was excluded from the system boundaries of this study, developing material banks is a key strategy (Luscuere 2017). Operating within a limited geographical radius, these hubs could connect deconstruction sites with new projects. Local authorities could play a pivotal role by mandating the use of materials from local deconstructed stocks for public buildings. This approach would not only reduce storage times by identifying buyers early but also stimulate market demand, creating a viable economic ecosystem for structural reuse.

## Sensitivity Analysis and Limitations

### *Sensitivity analysis*

Two sensitivity analyses were conducted to assess the robustness of the study's conclusions.

The first analysis examines the influence of a  $\pm 25\%$  variation in connection mass on environmental results. The findings demonstrate a strictly linear, proportional response, with variations of  $\pm 25\%$  across all connections and TRACI 2.1 indicators, confirming that mass is the primary determinant of environmental impacts, without threshold effects or complex interactions. Subsequent models show a progressive attenuation of variations, generally decreasing below 10% and then below 2%, with the notable exception of Ecotoxicity for the DTJ, which maintains a more pronounced sensitivity (17.3% and 5.32%, respectively).

The second analysis evaluates the influence of end-of-life environmental credit allocation methods. In the reference scenario, the benefits from recycling and energy recovery are equally distributed (50-50) between the studied and future systems, in accordance with ISO 21930:2017 recommendations. An alternative scenario attributing all benefits to the studied system (100-0) was simulated as well.

This methodological change generates substantial variations in absolute impacts, significantly greater than those observed for mass variation. The most sensitive indicators include Smog, Global Warming, and Eutrophication, particularly influenced by metal and wood production, with variations reaching up to 100% for certain connection-indicator combinations. The DTJ consistently proves to be the most sensitive connection to allocation assumptions. However, the relative ranking of connections remains unchanged between the two scenarios, with DTJ and BDJ solutions maintaining their positions as the least environmentally favorable options, demonstrating the robustness of the conclusions despite end-of-life allocation being a more critical source of uncertainty than mass variability.

### Limitations

Several limitations should be considered when interpreting the results.

One primary limitation concerns the system boundaries, which exclude the construction and deconstruction phases due to the lack of reliable inventory data. Similarly, post-deconstruction storage was omitted as storage duration is highly case-specific and difficult to simulate. Consequently, the environmental impact of the reuse process itself may be underestimated.

Regarding the reuse potential, the OPTI scenario assumes that materials are 100% reusable by design. Reductions in reuse rates (59 to 100% for connections; 65 to 69% for GLT) were solely attributed to mechanical damage induced by structural use. It is important to note that time-dependent degradation factors (*e.g.*, moisture) and chemical contamination were not modeled due to the absence of established quantification methodologies. Therefore, the reported reuse rates represent a maximum achievable theoretical potential; actual rates would likely be lower due to unquantified environmental weathering.

Beyond technical aspects, economic and regulatory constraints were also outside the scope of this assessment. As noted by Tura *et al.* (2019), high initial investment costs and rigid regulatory frameworks currently hinder the widespread adoption of reuse. Thus, the environmental benefits presented here assume a mature market for reused components that does not yet exist but is an intended objective.

From a design perspective, the study focused on standard connection designs rather than components specifically optimized for disassembly. While standard connections facilitate assembly, they do not necessarily maximize reusability. Future research should therefore integrate Design for Disassembly (DfD) principles to further validate these findings (Thormark 2006).

## CONCLUSIONS

1. The study confirms that excluding structural connections solely on the basis of a mass cut-off criterion (<1%) is methodologically flawed for timber buildings. Although their mass is negligible, connections contribute up to 3% of the building's initial embodied carbon. More critically, they possess a *high environmental significance* by dictating the end-of-life scenario of the structural system, thus invalidating their exclusion under ISO 14044 guidelines.
2. Structural connections function as the primary leverage point for the circularity of mass timber buildings. The comparison between standard (QUEB) and optimized (OPTI) scenarios demonstrates that the connection design determines whether massive timber components are reused or downcycled. A design focusing on ease of disassembly prevents the contamination of the wood resource (*e.g.*, by embedded screws). The Bridle joint appears to be the structural connection with the highest potential for reuse. In addition to enabling off-site prefabrication and easy on-site assembly, this solution reduces the structural impact of a timber-framed building by more than 7%.
3. Among the five systems analyzed, the Bridle Joint (BDJ) was identified as the most effective solution for circularity. Applying an optimistic reuse scenario to the connections and their associated timber elements resulted in a 7% to 16% reduction in

the building's total Global Warming Potential (GWP) for this specific design, significantly outperforming other solutions.

4. To activate the environmental benefits of reuse, future timber designs must integrate Design for Disassembly (DfD) principles at the connection level. The study highlights that standardization of the connection interface—rather than the entire building grid—offers a pragmatic pathway to make component reuse technically and logistically feasible.

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## APPENDIX

**Table S1.** Ecoinvent Process Used Throughout the Study

Ecoinvent Process
Bitumen seal, polymer EP4 flame retardant {CA-QC}  bitumen seal production, polymer EP4 flame retardant   Cut-off, U
Shale brick {CA-QC}  shale brick production   Cut-off, U
Cross-laminated timber {RER}  cross-laminated timber production   Cut-off, U
Concrete, 25MPa {CA-QC}  concrete production, 25MPa, for building construction, for interior use, with cement, Portland   Cut-off, U
Impact extrusion of steel, cold, 2 strokes {RoW}  impact extrusion of steel, cold, 2 strokes   Cut-off, U
Flat glass, uncoated {RoW}  flat glass production, uncoated   Cut-off, U
Glass wool mat {CA-QC}  glass wool mat production   Cut-off, U
Plywood, for outdoor use {CA-QC}  plywood production, for outdoor use   Cut-off, U
Gypsum fibreboard {GLO}  market for gypsum fibreboard   Cut-off, U
Gypsum plasterboard {GLO}  market for gypsum plasterboard   Cut-off, U
Hot rolling, steel {GLO}  market for hot rolling, steel   Cut-off, U
Metal working, average for steel product manufacturing {RoW}  metal working, average for steel product manufacturing   Cut-off, U
Plywood, for outdoor use {CA-QC}  plywood production, for outdoor use   Cut-off, U
Polystyrene, extruded {CA-QC}  polystyrene production, extruded, CO <sub>2</sub> blown   Cut-off, U
Steel wire rod {GLO}   blast furnace route and electric arc furnace route   production mix, at plant   1kg   LCI result
Glued laminated timber, average glue mix {CA-QC}  glued laminated timber production, average glue mix   Cut-off, U
Steel, chromium steel 18/8 {GLO}  market for steel, chromium steel 18/8   Cut-off, U
Transport, freight, lorry >32 metric ton, EURO4 {RoW}  transport, freight, lorry >32 metric ton, EURO4   Cut-off, U
Transport, freight, lorry >32 metric ton, EURO4 {RoW}  transport, freight, lorry >32 metric ton, EURO4   Cut-off, U
Transport, freight, sea, container ship {GLO}  transport, freight, sea, container ship   Cut-off, U
Transport, freight, lorry >32 metric ton, EURO5 {RER}  transport, freight, lorry >32 metric ton, EURO5   Cut-off, U
Sawnwood, board, softwood, dried (u=20%), planed {CA-QC}  planing, board, softwood, u=20%   Cut-off, U

**Table S2.** Model 1 LCA Characterized Results with TRACI 2.1 and QUEB Scenario – 2DF: Two-dimensional Fitting, 3DF: Three-dimensional Fitting, BDJ: Bridle-joint, DTJ: Dovetail-joint, 45S: 45° Screws

		2DF	3DF	BDJ	DTJ	45S
Ozone depletion (kg CFC-11 eq)	Steel production	1.37E-07	2.89E-07	1.54E-08	1.91E-07	5.34E-08
	Steel end-of-life	4.16E-10	1.63E-09	2.78E-11	4.70E-10	9.67E-11
	Aluminium production	0	0	0	2.90E-06	0
	Aluminium end-of-life	0	0	0	-2.02E-07	0
Global warming (kg CO <sub>2</sub> eq)	Steel production	1.77E+01	4.48E+01	1.32E+00	1.85E+01	4.58E+00
	Steel end-of-life	-1.09E+00	-4.29E+00	-7.13E-02	-1.20E+00	-2.48E-01
	Aluminium production	0	0	0	1.51E+02	0
	Aluminium end-of-life	0	0	0	6.93E+01	0
Smog (kg O <sub>3</sub> eq)	Steel production	1.17E+00	3.01E+00	7.98E-02	1.04E+00	2.77E-01
	Steel end-of-life	-2.76E-02	-1.08E-01	-1.83E-03	-3.10E-02	-6.37E-03
	Aluminium production	0	0	0	1.02E+01	0
	Aluminium end-of-life	0	0	0	-5.75E-01	0
Acidification (kg SO <sub>2</sub> eq)	Steel production	7.20E-02	1.80E-01	5.32E-03	7.04E-02	1.85E-02
	Steel end-of-life	-2.35E-03	-9.09E-03	-1.64E-04	-2.78E-03	-5.72E-04
	Aluminium production	0	0	0	9.36E-01	0
	Aluminium end-of-life	0	0	0	-7.45E-02	0
Eutrophication (kg N eq)	Steel production	2.16E-02	3.89E-02	3.21E-03	4.00E-02	1.11E-02
	Steel end-of-life	-7.17E-05	-2.73E-04	-5.22E-06	-8.82E-05	-1.81E-05
	Aluminium production	0	0	0	4.61E-01	0
	Aluminium end-of-life	0	0	0	-2.36E-02	0
Carcinogenics (CTUh)	Steel production	2.32E-06	4.15E-06	2.65E-07	2.73E-06	9.20E-07
	Steel end-of-life	6.12E-11	2.20E-10	5.20E-12	8.79E-11	1.81E-11
	Aluminium production	0	0	0	7.23E-05	0
	Aluminium end-of-life	0	0	0	-6.56E-06	0
Non carcinogenics (CTUh)	Steel production	2.49E-06	4.88E-06	3.13E-07	3.99E-06	1.09E-06
	Steel end-of-life	-2.33E-08	-8.45E-08	-1.95E-09	-3.29E-08	-6.76E-09
	Aluminium production	0	0	0	5.88E-05	0
	Aluminium end-of-life	0	0	0	-3.94E-06	0
Respiratory effects (kg PM <sub>2.5</sub> eq)	Steel production	9.21E-03	2.02E-02	9.68E-04	1.20E-02	3.36E-03
	Steel end-of-life	-1.56E-04	-6.14E-04	-1.02E-05	-1.72E-04	-3.54E-05
	Aluminium production	0	0	0	1.75E-01	0
	Aluminium end-of-life	0	0	0	-8.96E-03	0
Ecotoxicity (CTUe)	Steel production	1.46E+02	2.62E+02	1.99E+01	2.39E+02	6.88E+01
	Steel end-of-life	1.26E-02	6.85E-02	-2.28E-04	-3.86E-03	-7.93E-04
	Aluminium production	0	0	0	1.21E+04	0
	Aluminium end-of-life	0	0	0	-2.67E+02	0
Fossil fuel depletion (MJ surplus)	Steel production	1.45E+01	3.42E+01	1.16E+00	1.55E+01	4.01E+00
	Steel end-of-life	-3.43E-01	-1.26E+00	-2.76E-02	-4.66E-01	-9.59E-02
	Aluminium production	0	0	0	1.08E+02	0
	Aluminium end-of-life	0	0	0	-7.66E+00	0

**Table S3.** Model 2 LCA Characterized Results with TRACI 2.1 and QUEB Scenario – 2DF: Two-dimensional Fitting, 3DF: Three-dimensional Fitting, BDJ: Bridle-joint, DTJ: Dovetail-joint, 45S: 45° Screws

		2DF	3DF	BDJ	DTJ	45S
Ozone depletion (kg CFC-11 eq)	Wood production	8.49E-06	8.49E-06	1.03E-05	8.48E-06	8.48E-06
	Wood end-of-life	3.11E-07	3.11E-07	3.77E-07	3.11E-07	3.11E-07
	Steel production	1.37E-07	2.89E-07	1.54E-08	1.91E-07	5.34E-08
	Steel end-of-life	4.16E-10	1.63E-09	2.78E-11	4.70E-10	9.67E-11
	Aluminium production	0	0	0	2.90E-06	0
	Aluminium end-of-life	0	0	0	-2.02E-07	0
Global warming (kg CO2 eq)	Wood production	3.48E+02	3.48E+02	4.21E+02	3.47E+02	3.47E+02
	Wood end-of-life	4.16E+01	4.16E+01	5.04E+01	4.16E+01	4.16E+01
	Steel production	1.77E+01	4.48E+01	1.32E+00	1.85E+01	4.58E+00
	Steel end-of-life	-1.09E+00	-4.29E+00	-7.13E-02	-1.20E+00	-2.48E-01
	Aluminium production	0	0	0	1.51E+02	0
	Aluminium end-of-life	0	0	0	6.93E+01	0
Smog (kg O3 eq)	Wood production	5.19E+01	5.19E+01	6.29E+01	5.18E+01	5.18E+01
	Wood end-of-life	1.78E+01	1.78E+01	2.16E+01	1.78E+01	1.78E+01
	Steel production	1.17E+00	3.01E+00	7.98E-02	1.04E+00	2.77E-01
	Steel end-of-life	-2.76E-02	-1.08E-01	-1.83E-03	-3.10E-02	-6.37E-03
	Aluminium production	0	0	0	1.02E+01	0
	Aluminium end-of-life	0	0	0	-5.75E-01	0
Acidification (kg SO2 eq)	Wood production	2.01E+00	2.01E+00	2.43E+00	2.01E+00	2.01E+00
	Wood end-of-life	5.62E-01	5.62E-01	6.81E-01	5.62E-01	5.62E-01
	Steel production	7.20E-02	1.80E-01	5.32E-03	7.04E-02	1.85E-02
	Steel end-of-life	-2.35E-03	-9.09E-03	-1.64E-04	-2.78E-03	-5.72E-04
	Aluminium production	0	0	0	9.36E-01	0
	Aluminium end-of-life	0	0	0	-7.45E-02	0
Eutrophication (kg N eq)	Wood production	6.13E-01	6.13E-01	7.43E-01	6.12E-01	6.12E-01
	Wood end-of-life	3.15E+00	3.15E+00	3.82E+00	3.15E+00	3.15E+00
	Steel production	2.16E-02	3.89E-02	3.21E-03	4.00E-02	1.11E-02
	Steel end-of-life	-7.17E-05	-2.73E-04	-5.22E-06	-8.82E-05	-1.81E-05
	Aluminium production	0	0	0	4.61E-01	0
	Aluminium end-of-life	0	0	0	-2.36E-02	0
Carcinogenics (CTUh)	Wood production	3.61E-05	3.61E-05	4.37E-05	3.61E-05	3.61E-05
	Wood end-of-life	3.05E-06	3.05E-06	3.69E-06	3.05E-06	3.05E-06
	Steel production	2.32E-06	4.15E-06	2.65E-07	2.73E-06	9.20E-07
	Steel end-of-life	6.12E-11	2.20E-10	5.20E-12	8.79E-11	1.81E-11
	Aluminium production	0	0	0	7.23E-05	0
	Aluminium end-of-life	0	0	0	-6.56E-06	0
Non carcinogenics (CTUh)	Wood production	1.06E-04	1.06E-04	1.29E-04	1.06E-04	1.06E-04
	Wood end-of-life	9.02E-05	9.02E-05	1.09E-04	9.02E-05	9.02E-05
	Steel production	2.49E-06	4.88E-06	3.13E-07	3.99E-06	1.09E-06
	Steel end-of-life	-2.33E-08	-8.45E-08	-1.95E-09	-3.29E-08	-6.76E-09
	Aluminium production	0	0	0	5.88E-05	0
	Aluminium end-of-life	0	0	0	-3.94E-06	0
Respiratory effects (kg PM2.5 eq)	Wood production	4.46E-01	4.46E-01	5.41E-01	4.46E-01	4.46E-01
	Wood end-of-life	4.45E-02	4.45E-02	5.40E-02	4.45E-02	4.45E-02
	Steel production	9.21E-03	2.02E-02	9.68E-04	1.20E-02	3.36E-03
	Steel end-of-life	-1.56E-04	-6.14E-04	-1.02E-05	-1.72E-04	-3.54E-05

	Aluminium production	0	0	0	1.75E-01	0
	Aluminium end-of-life	0	0	0	-8.96E-03	0
Ecotoxicity (CTUe)	Wood production	4.04E+03	4.04E+03	4.89E+03	4.03E+03	4.03E+03
	Wood end-of-life	7.94E+02	7.94E+02	9.62E+02	7.94E+02	7.94E+02
	Steel production	1.46E+02	2.62E+02	1.99E+01	2.39E+02	6.88E+01
	Steel end-of-life	1.26E-02	6.85E-02	-2.28E-04	-3.86E-03	-7.93E-04
	Aluminium production	0	0	0	1.21E+04	0
	Aluminium end-of-life	0	0	0	-2.67E+02	0
Fossil fuel depletion (MJ surplus)	Wood production	6.95E+02	6.95E+02	8.42E+02	6.94E+02	6.94E+02
	Wood end-of-life	2.62E+01	2.62E+01	3.17E+01	2.62E+01	2.62E+01
	Steel production	1.45E+01	3.42E+01	1.16E+00	1.55E+01	4.01E+00
	Steel end-of-life	-3.43E-01	-1.26E+00	-2.76E-02	-4.66E-01	-9.59E-02
	Aluminium production	0	0	0	1.08E+02	0
	Aluminium end-of-life	0	0	0	-7.66E+00	0

**Table S4.** Model 3 LCA Characterized Results with TRACI 2.1 and QUEB Scenario – 2DF: Two-dimensional Fitting, 3DF: Three-dimensional Fitting, BDJ: Bridle-joint, DTJ: Dovetail-joint, 45S: 45° Screws

		2DF	3DF	BDJ	DTJ	45S
Ozone depletion (kg CFC 11 eq)	Wood production	2.67E-03	2.67E-03	3.24E-03	2.67E-03	2.67E-03
	Wood end-of-life	9.80E-05	9.80E-05	1.19E-04	9.80E-05	9.80E-05
	Steel production	8.63E-05	1.82E-04	9.70E-06	1.20E-04	3.36E-05
	Steel end-of-life	2.62E-07	1.03E-06	1.75E-08	2.96E-07	6.09E-08
	Aluminium production	0	0	0	1.83E-03	0
	Aluminium end-of-life	0	0	0	-1.27E-04	0
	Others production	1.03E-02	1.03E-02	1.03E-02	1.03E-02	1.03E-02
	Others end-of-life	-3.12E-04	-3.12E-04	-3.12E-04	-3.12E-04	-3.12E-04
Global warming (kg CO2 eq)	Wood production	1.10E+05	1.10E+05	1.33E+05	1.09E+05	1.09E+05
	Wood end-of-life	1.31E+04	1.31E+04	1.59E+04	1.31E+04	1.31E+04
	Steel production	1.12E+04	2.82E+04	8.32E+02	1.17E+04	2.89E+03
	Steel end-of-life	-6.87E+02	-2.70E+03	-4.49E+01	-7.56E+02	-1.56E+02
	Aluminium production	0	0	0	9.51E+04	0
	Aluminium end-of-life	0	0	0	4.36E+04	0
	Others production	5.95E+05	5.95E+05	5.95E+05	5.95E+05	5.95E+05
	Others end-of-life	2.10E+04	2.10E+04	2.10E+04	2.10E+04	2.10E+04
Smog (kg O3 eq)	Wood production	1.63E+04	1.63E+04	1.98E+04	1.63E+04	1.63E+04
	Wood end-of-life	5.61E+03	5.61E+03	6.80E+03	5.61E+03	5.61E+03
	Steel production	7.37E+02	1.90E+03	5.03E+01	6.55E+02	1.75E+02
	Steel end-of-life	-1.74E+01	-6.80E+01	-1.15E+00	-1.95E+01	-4.01E+00
	Aluminium production	0	0	0	6.43E+03	0
	Aluminium end-of-life	0	0	0	-3.62E+02	0
	Others production	5.27E+04	5.27E+04	5.27E+04	5.27E+04	5.27E+04
	Others end-of-life	1.31E+04	1.31E+04	1.31E+04	1.31E+04	1.31E+04
Acidification (kg SO2 eq)	Wood production	6.33E+02	6.33E+02	7.65E+02	6.33E+02	6.33E+02
	Wood end-of-life	1.77E+02	1.77E+02	2.15E+02	1.77E+02	1.77E+02
	Steel production	4.54E+01	1.13E+02	3.35E+00	4.44E+01	1.17E+01
	Steel end-of-life	-1.48E+00	-5.73E+00	-1.03E-01	-1.75E+00	-3.60E-01
	Aluminium production	0	0	0	5.90E+02	0
	Aluminium end-of-life	0	0	0	-4.69E+01	0
	Others production	3.22E+03	3.22E+03	3.22E+03	3.22E+03	3.22E+03
	Others end-of-life	4.03E+02	4.03E+02	4.03E+02	4.03E+02	4.03E+02
Eutrophication (kg N eq)	Wood production	1.93E+02	1.93E+02	2.34E+02	1.93E+02	1.93E+02
	Wood end-of-life	9.92E+02	9.92E+02	1.20E+03	9.92E+02	9.92E+02
	Steel production	1.36E+01	2.45E+01	2.02E+00	2.52E+01	6.99E+00
	Steel end-of-life	-4.52E-02	-1.72E-01	-3.29E-03	-5.56E-02	-1.14E-02
	Aluminium production	0	0	0	2.90E+02	0
	Aluminium end-of-life	0	0	0	-1.49E+01	0
	Others production	1.20E+03	1.20E+03	1.20E+03	1.20E+03	1.20E+03
	Others end-of-life	1.93E+03	1.93E+03	1.93E+03	1.93E+03	1.93E+03
Carcinogenics (CTUh)	Wood production	1.14E-02	1.14E-02	1.38E-02	1.14E-02	1.14E-02
	Wood end-of-life	9.61E-04	9.61E-04	1.16E-03	9.61E-04	9.61E-04
	Steel production	1.46E-03	2.61E-03	1.67E-04	1.72E-03	5.80E-04
	Steel end-of-life	3.86E-08	1.39E-07	3.28E-09	5.54E-08	1.14E-08
	Aluminium production	0	0	0	4.55E-02	0
	Aluminium end-of-life	0	0	0	-4.13E-03	0
	Others production	4.03E-01	4.03E-01	4.03E-01	4.03E-01	4.03E-01
	Others end-of-life	1.91E-03	1.91E-03	1.91E-03	1.91E-03	1.91E-03

Non carcinogenics (CTUh)	Wood production	3.34E-02	3.34E-02	4.06E-02	3.34E-02	3.34E-02
	Wood end-of-life	2.84E-02	2.84E-02	3.43E-02	2.84E-02	2.84E-02
	Steel production	1.57E-03	3.07E-03	1.97E-04	2.51E-03	6.87E-04
	Steel end-of-life	-1.47E-05	-5.32E-05	-1.23E-06	-2.07E-05	-4.26E-06
	Aluminium production	0	0	0	3.70E-02	0
	Aluminium end-of-life	0	0	0	-2.48E-03	0
	Others production	1.53E-01	1.53E-01	1.53E-01	1.53E-01	1.53E-01
	Others end-of-life	5.41E-02	5.41E-02	5.41E-02	5.41E-02	5.41E-02
Respiratory effects (kg PM2.5 eq)	Wood production	1.40E+02	1.40E+02	1.70E+02	1.40E+02	1.40E+02
	Wood end-of-life	1.40E+01	1.40E+01	1.70E+01	1.40E+01	1.40E+01
	Steel production	5.80E+00	1.27E+01	6.10E-01	7.56E+00	2.12E+00
	Steel end-of-life	-9.83E-02	-3.87E-01	-6.43E-03	-1.08E-01	-2.23E-02
	Aluminium production	0	0	0	1.10E+02	0
	Aluminium end-of-life	0	0	0	-5.64E+00	0
	Others production	7.24E+02	7.24E+02	7.24E+02	7.24E+02	7.24E+02
	Others end-of-life	7.12E+01	7.12E+01	7.12E+01	7.12E+01	7.12E+01
Ecotoxicity (CTUe)	Wood production	1.27E+06	1.27E+06	1.54E+06	1.27E+06	1.27E+06
	Wood end-of-life	2.50E+05	2.50E+05	3.03E+05	2.50E+05	2.50E+05
	Steel production	9.20E+04	1.65E+05	1.25E+04	1.51E+05	4.33E+04
	Steel end-of-life	7.94E+00	4.32E+01	-1.44E-01	-2.43E+00	-5.00E-01
	Aluminium production	0	0	0	7.62E+06	0
	Aluminium end-of-life	0	0	0	-1.68E+05	0
	Others production	1.05E+07	1.05E+07	1.05E+07	1.05E+07	1.05E+07
	Others end-of-life	8.15E+05	8.15E+05	8.15E+05	8.15E+05	8.15E+05
Fossil fuel depletion (MJ surplus)	Wood production	2.19E+05	2.19E+05	2.65E+05	2.19E+05	2.19E+05
	Wood end-of-life	8.25E+03	8.25E+03	9.99E+03	8.25E+03	8.25E+03
	Steel production	9.14E+03	2.15E+04	7.31E+02	9.77E+03	2.53E+03
	Steel end-of-life	-2.16E+02	-7.94E+02	-1.74E+01	-2.94E+02	-6.04E+01
	Aluminium production	0	0	0	6.80E+04	0
	Aluminium end-of-life	0	0	0	-4.83E+03	0
	Others production	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
	Others end-of-life	7.14E+04	7.14E+04	7.14E+04	7.14E+04	7.14E+04