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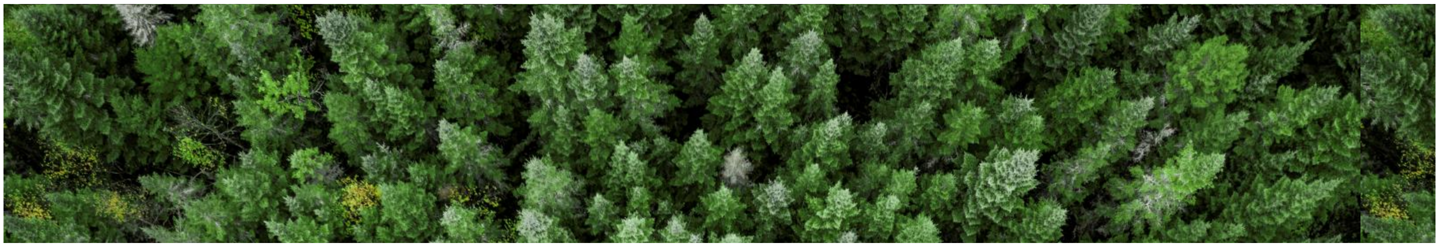
CLIMATE CHANGE AND ENVIRONMENTAL IMPACTS

Comparative life cycle assessment of resource road bridges

PROJECT NUMBER: 301014016



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1 CONTEXT & OBJECTIVES

FPInnovations' major project entitled "Climate Change and Environmental Impacts (CCEI)" aims at providing solutions for creating climate-resilient forest operations and reduced environmental impacts. To do so, several pathways are investigated including:

- Ensuring reliable and dependable access to fibre supply through,
    - resilient resource roads
    - resilient harvesting operations
- Understanding the vulnerabilities of forest operations to climate change,
- Mitigating the environmental impacts of the forest sector.

An important component of mitigating the environmental impacts of forest management is the knowledge and awareness of the environmental footprint of a product or process throughout its entire life cycle with the application of life cycle assessment (LCA). This knowledge is of interest to the forest sector as new products and technologies are evaluated and compared to historical practices for implementation in the roads and transportation segment of forest operations. This project segment is focused on two primary work areas:

(1) the operational and policy challenges of mitigating the impacts of forest operations on water quality and fish habitat, and

(2) furthering the understanding of the environmental footprint of products and processes being implemented by the forest sector.

The main objective of the present work is to respond to the second work area and complete LCAs focused on resource roads and transportation products and processes. Two LCA studies will be conducted; one study on resource road bridges and one study on hybridization of logging and biomass trucks. The present report undertakes an LCA of three resource road bridges.

This LCA task is financially supported by Natural Resources Canada.

2 TECHNICAL TEAM

The individuals who contributed to this LCA task on resource road bridges are listed below.

Name	Title, Group	Role
Mark Partington	Manager, Transportation & Infrastructure	Project leader
Aline Cobut	Researcher, Environment and Sustainability	Task leader
Patrick Lavoie	Senior scientist, Environment and Sustainability	Task support
Vincent Blanchard	Manager, Environment and Sustainability	Organizational alignment
Allan Bradley	Lead scientist, Transportation & Infrastructure	Technical support
Conroy Lum	Lead scientist, Building Systems	Technical support

3 GOAL AND SCOPE

3.1 Goal of the study

The goal of this study is to evaluate the comparative GHG emissions between different resource road bridge designs used in British Columbia (Canada) including:

- a conventional timber and steel bridge [1],
- a concrete and steel bridge [2], and
- a fiber-reinforced glue-laminated timber bridge [3].

Additional comparisons will be conducted on the type of reinforcements available for fiber-reinforced timber bridges to better grasp their environmental footprints and provide a preliminary overview of environmental cost versus structural benefits of such designs.

The primary intended audience are members of the Transportation and Infrastructure Group and more broadly FPInnovations' other interested parties, and members.

3.2 Scope of the study

3.2.1 Description of product systems

The selected bridges, referred in this report as product systems, are all single-span, single-lane bridges constructed on resource roads. Both the timber/steel bridge [1], and concrete/steel bridge [2] are typical designs used by B.C.'s Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRO&RD). The fiber-reinforced glulam timber bridge [3] is a less common design which was commissioned by B.C.'s FLNRO&RD and installed as a replacement bridge in 2019. Furthermore, the three designs are considered comparable [4]. As a side note, bridge clear span (centre of bearing to centre of bearing) will vary by topography of the crossing (depth and width of stream channel), optimal height of the road approaches, and any additional width needed to accommodate the abutments [4].

Key technical properties of the three bridge designs are presented in **Erreur ! Source du renvoi introuvable.**.

Table 1: Technical properties of the three studied bridges.

	Unit	System 1	System 2	System 3
Design load	-	L-100[1]		
Design service life	years	45	100	50
Length	m	21.3	21.2	30.5
Width	m	5.5	6.2	4.3
Surface area	m^2	117	130	130
Deck material(s)	-	Precast concrete	Glue-laminated timber	Timber
Superstructure material(s)	-	Weathering steel (I-beams	Fiber reinforced glue-laminated	Weathering steel (I beams

	Unit	System 1	System 2	System 3
		and plated steel elements)	timber (beams and blocking panels)	and plated steel elements)
Substructure material(s)	-	Steel piles with reinforced concrete footings and ballast walls	Glue-laminated timber abutments, backwall and footing panels	Assumed similar to system 1 (no data on drawing) [5]
Design standards	-	CAN/CSA S6 [6] and Forest Service Bridge Design and Construction Manual [7]		

[1]Corresponds to a gross vehicle weight load rating of 100 imperial tons which is equal to 91 metric tons.

The impact in design between a 20m- and 30m-long bridge steel substructure is considered minimal even negligible [8]. Therefore, for system 3 substructure, the use of system 1 substructure data has been assumed as a fair approximation.

A material breakdown of each bridge is presented in Figure 1, Figure 2, and Figure 3 for system 1, system 2 and system 3 respectively.

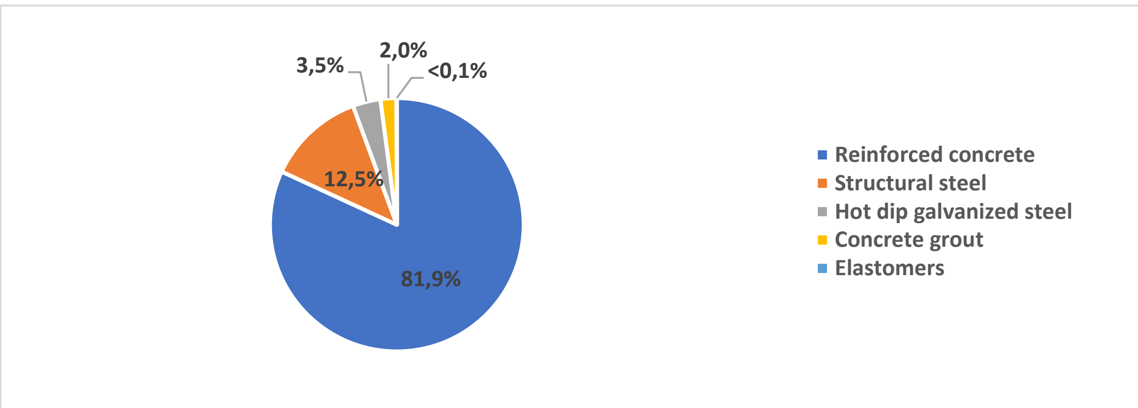

Figure 1: Material composition of system 1. Concrete deck with steel structure.

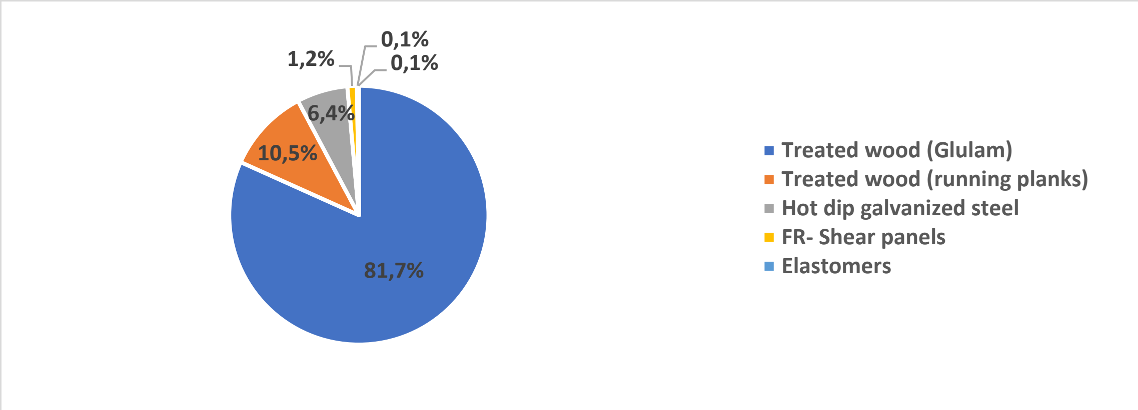

Figure 2: Material composition of system 2. Glulam deck and structure. "FR" stands for fiber reinforced.

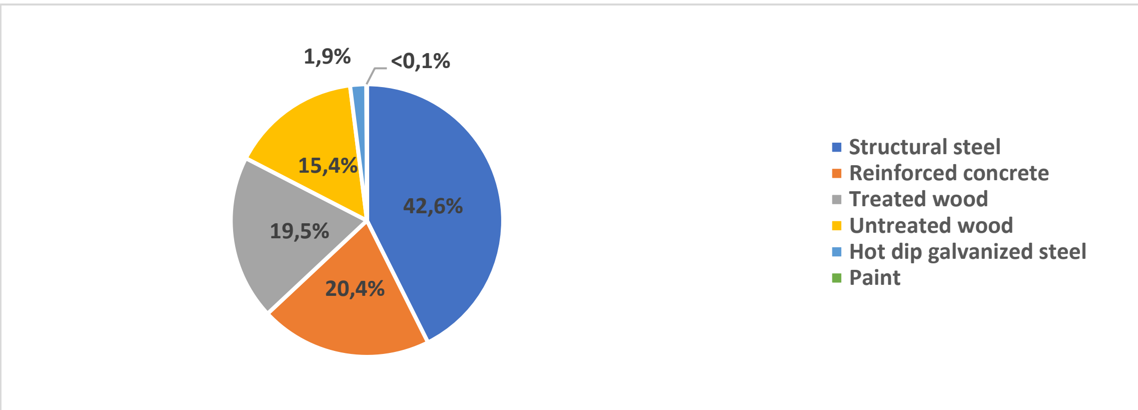

Figure 3: Material composition of system 3. Timber deck and steel structure.

3.2.2 Functional unit

The functional unit for the comparison of bridge designs is 1 square meter (m^2) of resource road bridge installed in the province of British Columbia (Canada) with a live load of L-100[1] and a reference service life of 45 years.

To convert the functional unit from "1 m^2" to "1 m", all reference flows (Section 5.2) and impact assessment results (Section 6.1) must be multiplied by the width of the respective system (cf. **Erreur ! Source du renvoi introuvable.**).

Other functions that may be linked to resource road bridges are not considered in this study: resistance to flooding or other natural disasters affecting forests, etc.

3.2.3 System boundaries

This study is a cradle-to-grave LCA and covers all life cycle stages for the studied bridges. More details about what is included or excluded are presented in

[1] Corresponds to a gross vehicle weight load rating of 100 imperial tons which is equal to 91 metric tons.

Table 2 below.

Table 2: Life cycle stages and related processes within the system boundaries for the studied systems and their equivalent as per ISO 21930:2017 [9].

Life cycle stages	ISO 21930:2017 equivalence	Included processes	Excluded processes	Reason for exclusion
Manufacturing of bridge elements	Production stage (modules A1 to A3)	- raw material extraction and production - transport of raw materials to bridge element manufacturing plant	- Manufacturing of approach slabs and rails - Manufacturing of bridge signs	- data available only for one design
Transport of bridge elements to building site	Construction stage (module A4)	- Road transportation	- None	- n/a
Construction of bridge	Construction stage (module A5)	- Use of machinery	- Traffic disturbance and re-routing - Road connection to bridge - Earthwork - Transportation of personnel	- Assumes no traffic disturbance nor re-routing observed for resource roads - Road connection and earthwork assumed similar
Maintenance, repair, and replacements	Use stage (modules B1 to B7)	- Machinery use - Raw materials needed for repair and/or replacement - Transport and treatment of resulting waste	- Inspections - Regular clean-ups of deck - Repair due to isolated events (e.g. road accidents or natural disasters) - Traffic disturbance and re-routing	- Inspections assumed similar - Regular clean ups assumed similar - Resource road bridges may be prone to higher risk of natural disasters due to their location but would have similar effect on both 3 systems - Traffic disturbance or need for re-routing are not observed on resource roads
End-of-life management	End-of-life stage (modules C1 to C4)	- Transport of bridge elements to treatment facilities (when applicable) - On-site treatment of waste (when applicable) - Emission related to waste treatment activities	- Demolition	- Demolition (e.g. transport of demolition equipment to bridge site) assumed similar for all systems
	Optional: benefits beyond system boundary (module D)		- Recycling of bridge elements	- Recycling of bridge elements is not common

3.2.3.1 Potential implications of exclusions on study results

The exclusion of approach slabs and rails are not expected to affect the study results. Even though approach slabs are presented in system 2 design (since designed for a specific site location), according to B.C.'s Ministry of Transportation and Infrastructure (MoTI), approach slabs are typically not required for low-volume road structures, such as resource road bridges. In the event, that the resource road bridge also serve a lifeline purpose for surrounding communities, approach slabs are needed [10]. In that case, if we consider all three systems installed at the same location, the approach slabs would be similar. Approach rails are also not mandatory but highly dependent on site location. Therefore, for a same location, same approach rails are likely to be built [11].

Road signs, road connection and earthwork fall into the same category as approach slabs and rails and are not expected to affect the study conclusions. For a same location, road connection and related road signs would be identical. Earthwork may differ a bit to accommodate different types of substructures but is expected to remain negligible.

The exclusion of traffic disturbance and re-routing are not expected to affect the study results in the context of resource roads. For bridges constructed on new forest roads, the construction would not create any disturbance or re-routing because they are accessing a resource that cannot be developed until the roads are in. For an existing bridge this could cause minor delays, but maintenance and repair activities are often scheduled for low use periods to minimize impacts to road users. More over forest road networks don't typically have much duplication of access so re-routing often isn't an option [12]. Where re-routing is expected, it is important to consider potential impacts from differences in construction time between bridge designs.

3.2.4 Representativeness

The three studied bridge designs were selected with the help of experts at FPInnovations. The designs, as well as life cycle parameters (Table 2), are considered representative of current resource-road bridge designs in BC for L-100, single lane spans 20-30 m in length (temporal, geographical and technological representativeness) . Similar bridges exist and are currently built and used by the forest industry on resource roads in the province of British Columbia (Canada).

3.2.5 Critical review

This report has been critically reviewed by an independent internal party.

This report is not intended to be disclosed to the public. If results are to be communicated publicly, a critical review shall be conducted by a panel of interested parties in order to decrease the likelihood of misunderstandings or negative effects on external interested parties [13].

4 METHODS

4.1 Impact assessment method and selected indicators

Global warming potential (GWP) 100 is used to evaluate GHG impacts in this assessment as implemented in TRACI v2.1 [14] which is based on Intergovernmental Panel on Climate Change (IPCC) [15].

4.2 Treatment of biogenic carbon

Bio-based materials originating from renewable resources, such as Canadian and American forests, contain biogenic carbon. The accounting of biogenic carbon uptake (or removals) and emissions during the life cycle follows ISO 21930:2017 [9] requirements. When entering the product system, the biogenic carbon flow is characterized in the life cycle impact assessment (LCIA) with - 1kg CO_2 eq. per kg CO_2 of biogenic carbon, and emissions of biogenic CO_2 shall be characterized with + 1kg CO_2 eq. per kg CO_2 of biogenic carbon using the GWP indicator [9].

4.3 Allocation and cut-off

In a manufacturing process where more than one type of product is generated, LCA models use allocation methods to attribute the environmental flows (inputs and outputs) from the shared manufacturing process to the co-products in order to get product-based inventory data.

No allocation was necessary for the bridge manufacturing stage. For background and upstream multifunctional processes, modeled with generic life cycle inventory data, the original allocation methods were used. EPDs are based on physical allocation and so is the U.S. LCI database. The ecoinvent APOS system model generally uses economic allocation where allocation is applied to recycled materials at the point where they have been processed into materials that can substitute other market products [16].

No cut-off criterion for material or energy input flows were applied. Exclusions are documented in Table 2.

4.4 Modeling software

SimaPro 9.0.0.48 from Pré Consultants [17] has been used for the modeling of studied product systems.

5 INVENTORY

5.1 Data collection

Assumptions on several aspects including bridge elements, reference service life, maintenance and repair parameters and end-of-life have been established with the help of experts at

FPInnovations, Associated Engineering and the FLNRO&RD all located in British Columbia. Pedneault et al[18] was also considered as a main source of data for this LCA in terms of maintenance schedules and estimated transport distances.

Material quantities for the bridge designs were based on three engineering designs representative of current bridge designs used on resource roads according to the FLNRO&RD [1-3].

For input materials, results from environmental product declarations for North American glue-laminated [19] timber, softwood plywood [20], softwood lumber [21] and precast concrete [22] have been used.

In bridge systems 2 and 3, pentachlorophenol (PCP) was used for preservative treatment for wood elements (glulam and timber) with a retention rate of 9.6 kg/m³ [1, 3]. PCP chemicals and PCP treatment at plant have been modeled based on the work of Bolin and Smith [23, 24].

Emissions from landfilling of wood and open burning of wood were calculated using factors from IPCC's guidelines for national greenhouse gas inventories [25, 26].

Existing databases, ecoinvent v3.5 APOS[2] [27] and U.S. LCI [28], were also used to develop the model.

5.2 Inventory description

5.2.1 Manufacturing of bridge elements

The quantity of bridge elements to be manufactured for systems 1, 2 and 3 are presented in Table 3, Table 4 and Table 5 respectively.

Table 3: Quantity of raw materials used in the manufacturing of bridge elements for system 1.

Input materials	Unit	Quantity	Quantity per m², 45-year service life
Reinforced concrete	**kg**	9,41E+04	8,04E+02
Structural steel	**kg**	1,44E+04	1,23E+02
Hot dip galvanized steel	**kg**	4,08E+03	3,48E+01
Concrete grout	**kg**	2,32E+03	1,98E+01
Elastomers	**kg**	3,16E+01	2,70E-01
Paint	**kg**	2,27E+01	1,94E-01

System 2 is glulam bridge reinforced with polymer composites in two places. Strips of composite laminates, made of epoxy and synthetic fibers (aramid), are placed between wood laminations during girder manufacturing. Shear panels are sandwich composites made of plywood sheets with a core of epoxy and woven glass fibers. Shear panels are placed on both sides of girder ends. As a sensitivity, two additional types of composite laminate strips will be considered for system 2. These variations are further presented in Section 7.2.2.

[2] Allocation at the point of substitution

Table 4: Quantity of raw materials used in the manufacturing of bridge elements for system 2.

Input materials	Unit	Quantity	Quantity per m², 45-year service life
Treated wood (Glulam)	**kg**	3,50E+04	1,21E+02
Treated wood (running planks)	**kg**	4,49E+03	1,55E+01
Hot dip galvanized steel	**kg**	2,72E+03	9,40E+00
FR- Shear panels (fibers: woven glass, matrix: epoxy)	**kg**	5,10E+02	1,76E+00
Elastomers	**kg**	5,60E+01	1,93E-01
FR- Composite laminate (fibers: aramid, matrix: epoxy)	**kg**	1,20E+01	4,16E-02
FR: fiber-reinforcement			

The engineering design for system 3 used to estimate the material quantities do not have a substructure. The steel substructure from system 1 was recommended as approximate [5].

Table 5: Quantity of raw materials used in the manufacturing of bridge elements for system 3.

Input materials	Unit	Quantity	Quantity per m², 45-year service life
Structural steel	**kg**	2,68E+04	1,86E+02
Reinforced concrete	**kg**	1,29E+04	8,89E+01
Treated wood	**kg**	1,23E+04	8,51E+01
Untreated wood	**kg**	9,73E+03	6,73E+01
Hot dip galvanized steel	**kg**	1,21E+03	8,36E+00
Paint	**kg**	2,27E+01	1,57E-01
Elastomers	**kg**	2,07E+01	1,43E-01

5.2.2 Transport of bridge elements to building site

Bridge elements are all assumed to be transported 250 km to the building site by a combination truck [18]. The inputs per system for this stage are detailed in Table 6.

Table 6: Inputs for transportation of bridge elements to building site in t.km for all three systems.

Studied system	Mode of transportation	Unit	Quantity	Quantity per m², 45-year service life
System 1	Truck	**t.km**	2,87E+04	2,45E+02
System 2	Truck	**t.km**	1,07E+04	3,69E+01
System 3	Truck	**t.km**	1,58E+04	1,09E+02

5.2.3 Construction of bridge

Construction activities are mainly linked to the use of machinery. Assumptions about the type of machinery used and the duration of the construction for all three bridges were based on the work of Pedneault et al. [18] for bridges of similar spans. An additional reference was used for system 2 since it had a documented photo narrative of its construction [29] which helped with the duration estimate. The duration in terms of machinery use and number of days for the construction stage are detailed in both Table 7 and Table 8.

Table 7: Duration of construction operations for all three systems under study and type of machinery used.

Type of machinery	Machinery use (hours/day)	Duration (days)		
		System 1	System 2	System 3
Machinery < 18.64 kW	12	7	9	7
Machinery ≥ 18.64 kW and < 74.57 kW	6			
Machinery ≥ 74.57 kW	2			

Table 8: Total machinery use per type of machinery for all three systems.

Type of machinery	Total machinery use (hours)			Total machinery use (hours/m², 45-year service life)		
	System 1	System 2	System 3	System 1	System 2	System 3
Machinery < 18.64 kW	84	108	84	7,18E-01	3,73E-01	5,81E-01
Machinery ≥ 18.64 kW and < 74.57 kW	42	54	42	3,59E-01	1,86E-01	2,90E-01
Machinery ≥ 74.57 kW	14	18	14	1,20E-01	6,21E-02	9,68E-02

5.2.4 Maintenance, repair, and replacements

Assumptions about maintenance and repair schedules for all three bridges are based on Pedneault et al. [18], Maldonado and Bowman [30], Cecobois' guide [31], as well as communications with FPInnovations' experts[32]. Details about the types of repairs and maintenance applied to all three systems are presented in Table 9, Table 10 and Table 11 for system 1, system 2 and system 3 respectively.

Table 9: Maintenance and repair schedules for system 1.

Type of repair	Frequency	Type of machinery and hours of use	Input material
Repairs			
Resurfacing of concrete deck	every 25 years for 18 days (3 days of machinery use)	machinery < 18.64 kW (12h/day) machinery ≥ 18.64 kW and < 74.57 kW (6h/day)	20% of concrete deck materials (concrete and rebars)
Replacements			
Sealant (grout)	every 5 years (1 day of machinery use)	machinery < 18.64 kW (12h/day)	Initial grout input (Table 3)
Curbs/curb rails due to logging truck impacts	2x per year	-	5% of initial rails

Table 10: Maintenance and repair schedule for system 2.

Type of repair	Frequency	Type of machinery and hours of use	Input material
Replacements			
Running planks and glulam curbs	every 10 years (2 days of machinery use) every 20 years for glulam curbs and curb rails	machinery < 18.64 kW (12h/day)	Initial timber and hardware for running planks/curbs input (Table 4)
Repairs			

Type of repair	Frequency	Type of machinery and hours of use	Input material
Curbs/curb rails due to logging truck impacts	2x per year	-	5% of initial rails hardware only

Table 11: Maintenance and repair schedule for system 3.

Type of repair	Frequency	Type of machinery and hours of use	Input material
Replacements			
Whole timber deck	every 20 years for 4 days	machinery < 18.64 kW (12h/day) machinery ≥ 18.64 kW and < 74.57 kW (6h/day)	Initial timber deck input (Table 5; including hardware)
Running planks and wooden curbs	every 10 years (2 days of machinery use)	machinery < 18.64 kW (12h/day)	Initial timber and hardware for running planks/curbs input (Table 5)
Repairs			
Curbs/curb rails due to logging truck impacts	2x per year	-	5% of initial rails (hardware and timber)

5.2.5 End-of-life management

End-of-life management scenarios for different materials are based on recommendations from FLNRO&RD [33], and FPInnovations' experts [32] (see Table 12). The assumed distance between the building site and treatment centers was 250km [18].

Table 12: Typical waste treatment for bridge elements.

Type of building material	Waste treatment
Reinforced concrete	Landfill
Treated wood products	Sanitary landfill
Steel (structural and hardware)	Sorting center
Untreated wood	Buried on site (85%) Burned on site (15%)
Elastomers	Landfill

For biogenic carbon emission calculations, parameters from IPCC [34, 35] and U.S. EPA's WARM model [36] for landfilling and open burning have been used (Table 13).

Table 13: Key parameters for biogenic carbon emissions regarding landfilling and open burning of wood products.

Type of wood product	Waste treatment	Key parameters
Treated wood products	Sanitary landfill	DOCf[1]: 0.06 OX[2]: 0.1 Methane recovery: 47%
Untreated wood	Buried on site (85%)	DOCf[1]: 0.06 OX[2]: 0.1 Methane recovery: 0%
Untreated wood	Burned on site (15%)	OF_{CO2}[3]: 0.71 EF_{CH4}[4]: 6500 g/ton (wet waste) EF_{N2O}[5]: 150 g/ton (dry waste)

[1]*DOCf: fraction of degradable organic carbon that decomposes*
[2]*OX: landfill layer oxidation factor*
[3]*OF_{CO2}: oxidation factor for municipal solid waste, as default (% of carbon input)*

Type of wood product	Waste treatment	Key parameters
[4]EF_{CH4}: CH_4 emission factor of municipal solid waste, as default		
[5]EF_{N2O}: N_2O emission factor of agricultural waste, as default		

5.3 Data quality assessment

A qualitative data quality assessment has been conducted for this work. All unit processes and their representativeness in terms of reliability, completeness, time, geography and technology are presented in

ANNEX 1.

6 RESULTS

6.1 Biogenic Carbon

Biogenic carbon emissions and removals for system 2 and system 3, both containing wood products, are presented in Table 14 and Table 15. The inventory is broken down per life cycle stages and modules as per ISO 21930:2017 [9].

Table 14: Biogenic carbon emissions and removals, and net GWP, for system 2, per functional unit (1m² over 45 years).

		Production stage			Construction stage		Use stage							End-of-life stage			
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
		X	X	X	X	X	MND	X	X	X	MND	MND	MND	MND	X	X	X
BCRP	kg CO_2 eq	2,19E+02							1,10E+02	2,23E+02							
BCEP	kg CO_2 eq			1,42E+02					2,14E+01	4,32E+01							4,26E+01
Net GWP: - 3,03E+02 kg CO_2 eq.																	
X: included in LCA *MND: Module not declared*																	

BCRP: biogenic carbon removal from product; BCEP: biogenic carbon emission from product.

Table 15: Biogenic carbon emissions and removals, and net GWP, for system 3, per functional unit (1m² over 45 years).

		Production stage			Construction stage		Use stage							End-of-life stage			
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
		X	X	X	X	X	MND	X	X	X	MND	MND	MND	MND	X	X	X
BCRP	kg CO_2 eq	2,43E+02							2,92E+02	5,09E+02							
BCEP	kg CO_2 eq			4,01E+02					1,44E+02	2,11E+02							7,93E+01
Net GWP: -2,09E+02 kg CO_2 eq.																	
X: included in LCA *MND: Module not declared*																	

BCRP: biogenic carbon removal from product; BCEP: biogenic carbon emission from product.

6.2 Life cycle impact assessment

The GWP results for all three bridges are presented in Figure 4. System 2 has the lowest GWP compared to the other two systems. System 1 has the highest GWP.

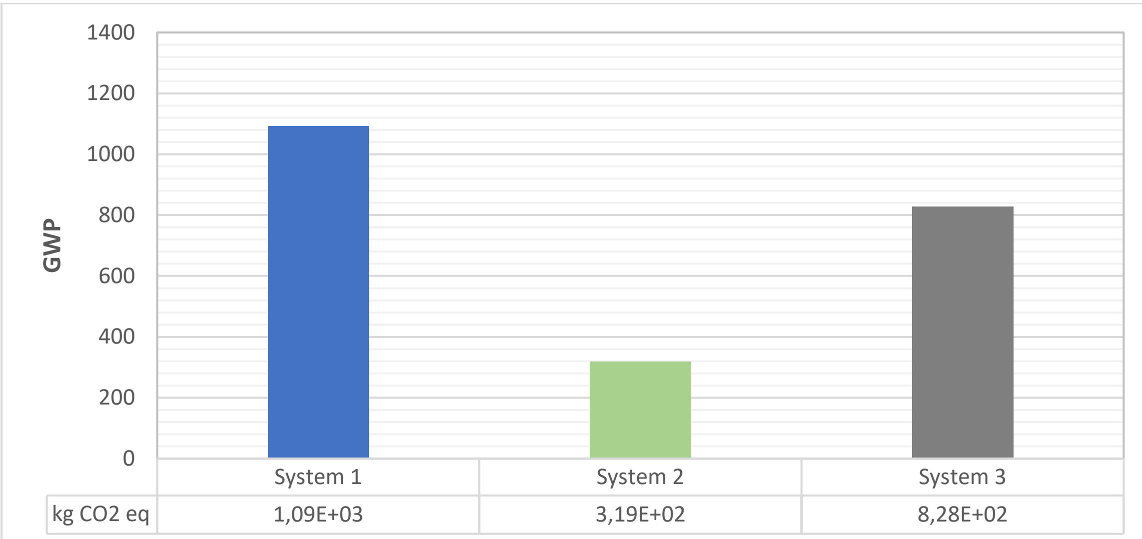

Figure 4: Cradle-to-grave GWP, excluding biogenic carbon emissions and removals, of all studied systems per functional unit.

Finally, Figure 5 presents the GWP results for all systems with the inclusion of biogenic carbon for systems 2 and 3. For details on how biogenic carbon is calculated, please refer to Sections 4.2 and 6.1. The trend observed before applying the biogenic carbon calculations is maintained and system 2 still has the lowest GWP, followed by system 3, system 2 having the highest GWP.

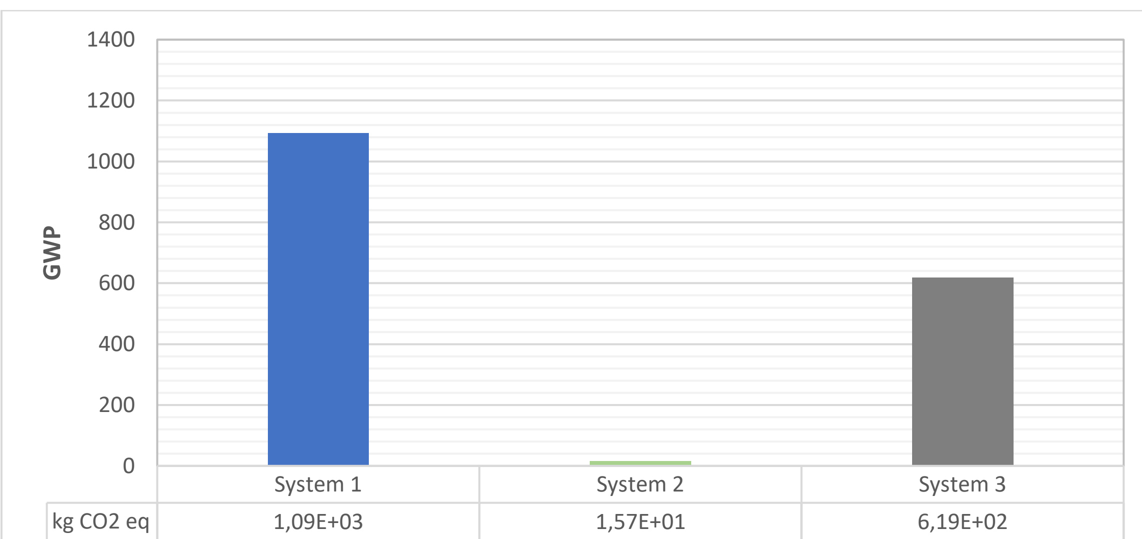

Figure 5: Cradle-to-grave GWP, including biogenic carbon emissions and removals, of all studied systems per functional unit.

6.3 Interpretation

Figure 6 presents the relative contribution of the different life cycle stages to the total GWP result for each bridge.

For systems 1 and 3, the manufacturing of bridge elements is the main contributor to the GWP followed by the "maintenance and repair" stage and the end-of-life management. For system 2, the "maintenance and repair" stage is the main contributor to the GWP followed by the manufacturing of bridge elements and the end-of-life management. Transportation of bridge elements to the building site has the smallest GWP construction for all bridges.

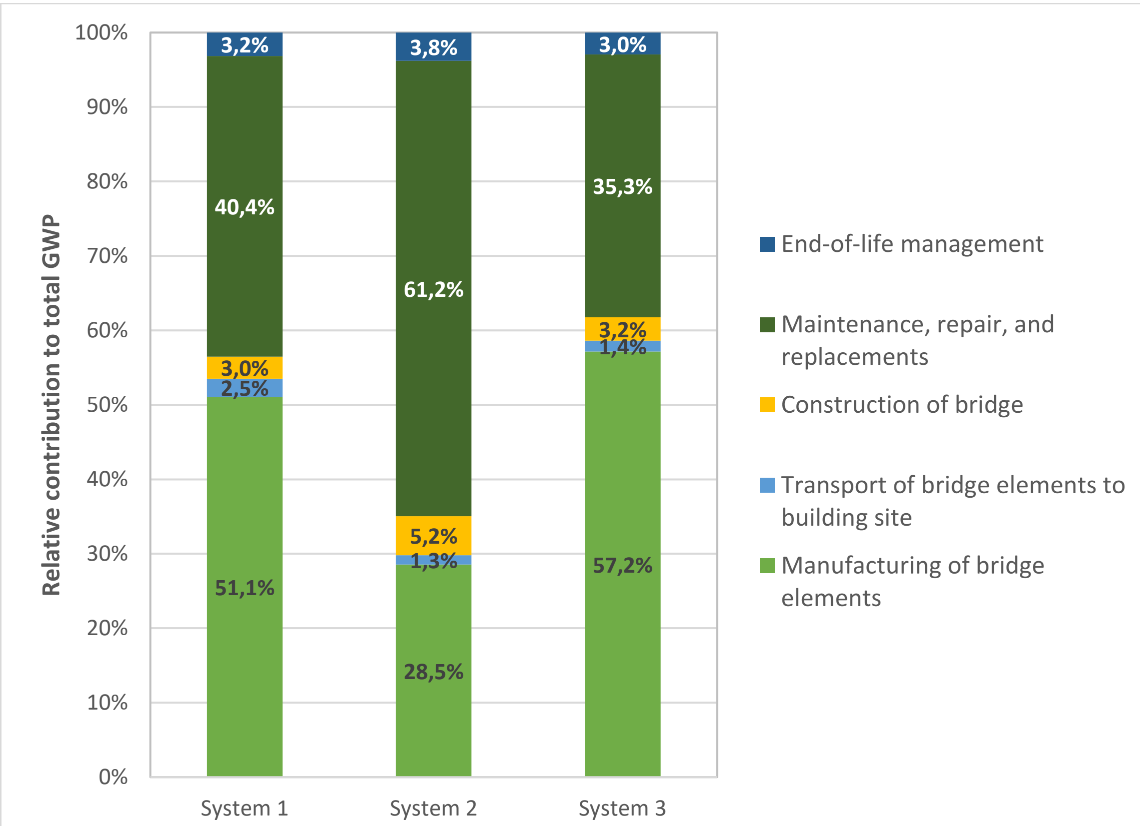

Figure 6: Relative contribution of cradle-to-grave life stages to the system total GWP, for the three studied systems.

For the manufacturing stage, the main GWP impacts for system 1 are due to the steel structure and reinforced concrete; glulam for system 2; and the steel structure for system 3. Steel and reinforced concrete are two energy intensive materials to produce compared to wood products, hence the lowest contribution of wood products to total GWP for systems containing wood products.

For system 1 and system 2, the main impact for "maintenance and repair" was the input of material (steel or treated wood, respectively). For system 3, transportation of waste to treatment facilities as a result of maintenance activities has the main contribution to GWP.

For all systems, the main contributor to the impact of the end-of-life management was the transportation of waste materials to treatment facilities.

7 UNCERTAINTY AND SENSITIVITY ANALYSES

7.1 Uncertainty analysis

Inventory data uncertainty has been implemented using two approaches, the ecoinvent default approach [37] for literature data, and, coefficients of variation, 2.5%, 12.5% and 25% for foreground estimations with high, medium and low reliability respectively.

It is important to note that ecoinvent datasets include uncertainty factors by default, while EPDs and U.S. LCI do not.

Uncertainty results for GWP were calculated using Monte Carlo (Table 16) in a comparative setup (1000 iterations). Systems were compared pairwise, A vs. B, to determine the probability of occurrence of a lower or higher GWP. From Table 18, the trend of results is confirmed, in 100% and 99.7% of iterations, system 1 has a higher GWP than system 2 and system 3, respectively. Besides, system 3 has a higher GWP than system 2 for 100% of iterations.

Table 16: Monte Carlo comparative results, A minus B, for each bridge design.

B / A	Environmental indicator	System 2	System 3
System 1	GWP	A ≥ B 100%	A ≥ B 99.7%
System 2	GWP	-	A < B 100%

Other sources of uncertainty such as, the impact assessment method (characterization factors), different types of fiber reinforcements, the influence of service life and design life, the end-of-life management of concrete and steel elements, were investigated in the sensitivity analysis (Section 7.2).

7.2 Sensitivity analysis

7.2.1 Impact assessment method

Using another environmental impact assessment (EIA) method limits the results uncertainty due to the uncertainty linked to characterization factors, which are specific to each EIA method. For this work, the method IPCC 2013 GWP100 has been used.

In this case, the result trend did not change with the use of this alternative EIA method.

7.2.2 Fiber reinforcement of system 2

As a sensitivity, two additional types of fiber reinforcement are considered for system 2. These variations are referred to in Table 17 as composite laminate (CL) #1, CL #2, and CL #3).

Table 17: Quantity of raw materials used in the manufacturing of bridge elements for system 2.

Input materials	Unit	Quantity CL#1	Quantity CL#2	Quantity CL#3	Quantity CL#1 per m², 45-year service life	Quantity CL#2 per m², 45-year service life	Quantity CL#3 per m², 45-year service life
Treated wood (Glulam)	**kg**	3,50E+04	3,50E+04	3,50E+04	1,21E+02	1,21E+02	1,21E+02
Treated wood (running planks)	**kg**	4,49E+03	4,49E+03	4,49E+03	1,55E+01	1,55E+01	1,55E+01
Hot dip galvanized steel	**kg**	2,72E+03	2,72E+03	2,72E+03	9,40E+00	9,40E+00	9,40E+00
FR- Shear panels	**kg**	5,10E+02	5,10E+02	5,10E+02	1,76E+00	1,76E+00	1,76E+00
Elastomers	**kg**	5,60E+01	5,60E+01	5,60E+01	1,93E-01	1,93E-01	1,93E-01
FR- CL#1 (Fiber: aramid, matrix: epoxy)	**kg**	1,20E+01	-	-	4,16E-02	-	-
FR- CL#2 (Fiber: glass-aramid, matrix: epoxy)	**kg**	-	4,32E+01	-	-	1,49E-01	-
FR- CL#3 (Fiber: carbon-aramid, matrix: epoxy)	**kg**	-	-	1,23E+01	-	-	4,24E-02
FR: fiber-reinforcement; CL: composite laminate.							

Table 18 presents the variation in GWP for the different types of reinforcement used in the glulam structure. The difference in terms of GWP result is negligible (<1%) for the three different types of reinforcements.

Table 18: GWP of studied variations of system 2 (three different fiber reinforcements) per m² bridge surface area.

Environmental impact category	Unit	System 2, CL#1	System 2, CL#2	System 2, CL#3
GWP	kg CO_2 eq.	3,63E+02	3,64E+02	3,63E+02

7.2.3 Design life of resource road bridges

7.2.3.1 75-year design life

According to FNLRO&RD [38], system 1 and system 3 designs could last 75 years instead of 45 years or 50 years, respectively. System 2 has a design life of 100 years which is extraordinary in a Canadian context. A more reasonable design life for glulam bridges would likely be 60 to 75 years. In that sense, the impact of a similar design service life of 75 years for all three systems to fulfil the functional unit (45 years of service life) is investigated. Table 19 presents the applied parameters for this sensitivity analysis.

Table 19: Applied parameters for sensitivity on 75-year design life of the three bridge systems.

Studied system	Design life	Service life for Functional unit	Original reference flow for inventory data	75-year design life (sensitivity)	Modified reference flow for inventory data (sensitivity)
System 1	45	45	45/45	75	45/45 multiplied by 45/75, except "maintenance and repair"
System 2	100	45	45/100	75	45/100 multiplied by 100/75 except "maintenance and repair"
System 3	50	45	45/50	75	45/50 multiplied by 50/75 except "maintenance and repair"

With this hypothesis, the result trend remained unchanged even though the GWP results of system 1 and system 3 were reduced (-27.3% and -23.2% respectively), whereas GWP result for system 2 has increased (+15.4%) when compared to the original GWP results (Figure 4).

7.2.3.2 45-year design life

The effect on all three systems of changing the design life to match a 45-year service life is assessed here. In that sense, the impact assessment results for all three systems having the same design service life of 45 years to fulfil the functional unit (45 years of service life) is investigated. Table 20 presents the applied parameters for this sensitivity analysis.

Table 20: Applied parameters for sensitivity on 45-year design life of the three bridge systems.

Studied system	Design life	Service life for Functional unit	Original reference flow for inventory data	45-year design life (sensitivity)	Modified reference flow for inventory data (sensitivity)
System 1	45	45	45/45	45	-
System 2	100	45	45/100	45	45/100 multiplied by 100/45 except "maintenance and repair"
System 3	50	45	45/50	45	45/50 multiplied by 50/45 except "maintenance and repair"

With this hypothesis, the result trend was not changed even though the GWP results of system 2 and system 3 were higher (+57% and +8% respectively) than original GWP results (Figure 4). GWP result remained unchanged for system 1 since it already had a 45 year-service life.

7.2.4 System expansion for recycled bridge elements

No recycling or reuse of bridge elements is considered at the end of life. However, structural steel, like girders and plates, might be reused if they are still mechanically sound. Reinforcing concrete is also considered to be landfilled but could be recycled and crushed for further applications and most of rebars reclaimed. The effect of considering the avoided production of gravel, reinforcing steel, and hot-rolled low-alloyed steel within the system boundaries is investigated for system 1 and system 3. Recycled elements for both systems as well as the substituted materials are presented in Table 21.

Table 21: List of recycled bridge elements considered in the system expansion for systems 1 and 3 as well as the resulting avoided material production.

Studied system	Recycled bridge elements	Recycled material	Avoided material production	Notes
System 1	Reinforced concrete (100%)	Concrete (100%)	Crushed gravel	
		Rebars (95%)	Reinforcing steel	The remaining 5% are landfilled
	Steel structure (50%)	Hot-rolled low-alloyed steel	Hot-rolled low-alloyed steel	Remaining 50% are sent to treatment facilities
System 3	Steel structure (50%)	Hot-rolled low-alloyed steel	Hot-rolled low-alloyed steel	Remaining 50% are sent to treatment facilities

As a result, system expansion outcomes are following the main conclusions and do not provide a shift in the result trend for the three systems. However, the GWP results for systems 1 and 3 are significantly lower with system expansion (< 10%) when compared to the original GWP results (Figure 4). A key assumption in these sensitivity results is that the GHG intensity of avoided material production (e.g. CO_2eq per tonne of hot-rolled low-alloy steel) at the end of the service life (e.g. 45 years) is assumed to be equivalent to the GHG intensity of current material production. This may not be the case because of differences in the GHG intensity of energy used to produce these products as manufacturing reduce GHG emissions, and as manufacturing inputs change (e.g. more recycled steel is available to produce hot-rolled steel).

8 LIMITATIONS

The uncertainty surrounding the life expectancy of bridge elements on resource roads is a limitation and directly affects maintenance schedules for all systems and indirectly their environmental footprint. No repair was assumed for the glulam structure (girders and abutments) for the 45-year service life just like the steel structure for the other systems. The concrete deck for system 1 had repair activities but no deck replacement which may be necessary for a service life longer than 45 years as in the sensitivity analysis.

The maintenance and repair schedules were mainly based on information from the Province of Quebec (Canada) for non-resource road bridges (both in urban and rural areas) instead of resources roads in British Columbia. Non-resource road bridges are installed on higher volume roads with higher traffic which may have more repair and replacement compared to resource road bridges if traffic volume is an important cause of repair and replacement requirements relative to other causes such as climate. Lower repair and maintenance requirements on resource road bridges could decrease the GWP of this stage. Additional work may be needed to better understand which activities could be revised.

The sensitivity for material substitution at the end of life assumes that GHG emissions from substitute materials (steel and gravel) are the same in the future as the are today. However, global efforts to reduce GHG emissions could reduce GHG emissions from substitute materials in the future which would overestimate the potential for GHG reductions from substitution at the end of life. Also, as global steel or concrete stocks stabilize overtime, it becomes more likely that steel scrap or crushed concrete avoids the need for other recycled material thus eliminating any potential substitution benefit. Sensitivity results presented in this assessment could therefore over-estimate potential avoided GHG emissions from recycling. It is also possible to evaluate substitution effects at the manufacturing stage which can be important for steel products. For steel products, the limited supply of recycled steel implies that new steel demand must be produced through the virgin (basic oxygen furnace) route which has higher GHG impacts compared to recycled steel [39].

Data used in the assessment adopts different allocation methods which can affect the results. At this time, it is impractical to evaluate a single allocation approach due to differences in data sources.

For comparing the environmental performance of different products, it is important to consider several environmental impact categories. Considering multiple environmental indicators could result in different conclusions compared to those presented in this report. Being out of scope for this LCA, further analysis with additional environmental impact categories should be carried out to be able to provide a more complete assessment the three bridge designs.

Finally, this report is not intended to be disclosed to the public. If results are to be communicated publicly, a critical review shall be conducted by a panel of interested parties in order to decrease the likelihood of misunderstandings or negative effects on external interested parties.

9 CONCLUSIONS & RECOMMENDATIONS

This comparative LCA assessed the global warming potential of three different resource road bridge designs used in the province of British Columbia (Canada).

The results showed that glulam bridges have a lower GWP concrete and steel or timber and steel bridge designs. Conventional timber and steel bridges were also found to have a lower GWP compared to concrete deck bridges.

Future work is recommended to assess the sensitivity of the study findings when using the ecoinvent “Cut-Off” or “Recycled Content” allocation approach instead of allocation at the point of substitution specifically for bridge elements with recycled content.

Additional work could be done to include environmental impact categories other than global warming potential. This will not only enable a more comprehensive comparison of the three bridges environmental impacts, but also provide a better understanding of their environmental footprint.

Further research could also be done to determine the frequency of repair and replacements really needed on resource road bridges considering their specific context. Having a more specific portrait for this life cycle stage would lead to a more accurate representation of GHG emissions. It would be interesting to know how it will affect the three different bridge systems and this study findings.

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ANNEX 1

Data quality assessment of datasets used in the modeling of the three bridge systems. Based on FPInnovations' guidance [40].

					Pedigree matrix				
	Full name of chosen unit process	**Original/Adapted/ Created dataset**	**Geography**	**Time period of dataset**	**Reliability**	**Completeness**	**Time-related**	**Geography**	**Technology**
1. Raw material acquisition & transformation									
Pre-cast concrete slabs	z. Precast structural concrete_IW-EPD, US&Canada	Created	US & Canada	2016	2	3	2	2	2
Concrete deck grout (stud pockets in panels, joints between panels)	Cement mortar {RoW}| production | APOS, U	Original	Rest of World (excl. CH)	1994	3	4	5	3	3
Steel girders + other structural steel element (low carbon steel)	Steel, low-alloyed, hot rolled {RoW}| production | APOS, U	Original	Rest of World (excl. RER)	2000	3	4	5	3	3
Hot dip galvanized steel (parts, hardware)	Zinc coat, pieces {RoW}| zinc coating, pieces | APOS, U	Original	Rest of World (excl. RER)	1996	3	4	5	3	2
	Steel, low-alloyed, hot rolled {RoW}| production | APOS, U	Original	Rest of World (excl. RER)	2000	3	4	5	3	3
Composite laminates									
Fiber: aramid	Nylon 6-6 {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	4
Matrix: epoxy	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | APOS, U	Original	Rest of World (excl. RER)	2011	3	4	3	3	3
Fiber: glass-aramid	Nylon 6-6, glass-filled {RoW}| production | APOS, U	Original	Rest of World (excl. RER)	1996	3	4	5	3	4
Fiber: carbon-aramid	Acrylonitrile {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	4
	Nylon 6-6 {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	4
FR- Shear panels									
Fiberglass woven fabric	Glass fibre {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	3

	Full name of chosen unit process	Original/Adapted/ Created dataset	Geography	Time period of dataset	Pedigree matrix				
					Reliability	Completeness	Time-related	Geography	Technology
Epoxy resin	Epoxy resin, liquid {RoW}| market for epoxy resin, liquid | APOS, U	Original	Rest of World (excl. RER)	2011	3	4	3	3	3
Plywood	z. Softwood plywood, RNA_EPD	Created	US & Canada	2012	2	3	2	2	2
Paint, for steel struture (abutments only according to design)	Alkyd paint, white, without solvent, in 60% solution state {RoW}| alkyd paint production, white, solvent-based, product in 60% solution state | APOS, U	Original	Rest of World (excl. RER)	1995	3	4	5	3	3
Elastomers	Synthetic rubber {RoW}| production | APOS, U	Original	Rest of World (excl. RER)	1995	3	4	5	3	3
Untreated wood, softwood timber	z. Softwood lumber, RNA_EPD	Created	US & Canada	2018	2	3	2	2	2
Untreated wood, glulam timber	z. Glulam, RNA_EPD	Created	US & Canada	2018	2	3	2	2	2
PCP treatment	z. Wood treatment, PCP pressure treated, vacuum process/kg/RNA	Adapted	US	2010	2	4	4	3	2
2. Raw materials transportation to building site									
Road transportation by combination truck	Transport, combination truck, short-haul, diesel powered/tkm/RNA	Original	US	2010	2	4	4	3	2
3. Construction									
use of machinery < 18.64 kW (12h/day, MTQ 2019)	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| machine operation, diesel, < 18.64 kW, steady-state | APOS, U	Original	Global	2014	2	4	3	3	2
use of machinery ≥ 18.64 kW and < 74.57 kW (6h/day, MTQ 2019)	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | APOS, U	Original	Global	2014	2	4	3	3	2
use of machinery ≥ 74.57 kW (2h/jour, MTQ 2019)	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | APOS, U	Original	Global	2014	2	4	3	3	2
4. Operation: Maintenance, repair									
use of machinery < 18.64 kW (12h/day, MTQ 2019)	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| machine operation, diesel, < 18.64 kW, steady-state | APOS, U	Original	Global	2014	2	4	3	3	2

	Full name of chosen unit process	Original/Adapted/ Created dataset	Geography	Time period of dataset	Pedigree matrix				
					Reliability	Completeness	Time-related	Geography	Technology
use of machinery ≥ 18.64 kW and < 74.57 kW (6h/day, MTQ 2019)	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | APOS, U	Original	Global	2014	2	4	3	3	2
use of machinery ≥ 74.57 kW (2h/jour, MTQ 2019)	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | APOS, U	Original	Global	2014	2	4	3	3	2
Untreated wood, softwood timber	z. Softwood lumber, RNA_EPD	Created	US & Canada	2018	2	3	2	2	2
Untreated wood, glulam timber	z. Glulam, RNA_EPD	Created	US & Canada	2018	2	3	2	2	2
PCP treatment	z. Wood treatment, PCP pressure treated, vacuum process/kg/RNA	Adapted	US	2010	2	4	4	3	2
Concrete deck grout (stud pockets in panels, joints between panels)	Cement mortar {RoW}| market for cement mortar | APOS, U	Original	Rest of World (excl. CH)	2011	3	4	3	3	3
Hot dip galvanized steel (parts, hardware)	Zinc coat, pieces {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	2
	Steel, low-alloyed, hot rolled {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	3
Concrete	Concrete, 35MPa {GLO}| market for | APOS, U	Original	Global	2006	3	4	4	3	2
Rebar	Reinforcing steel {GLO}| market for | APOS, U	Original	Global	2011	3	4	3	3	2
Road transportation by truck of waste	Transport, light commercial truck, diesel powered/tkm/RNA	Original	US	2010	2	4	4	3	2
Waste treatment of concrete	Waste reinforced concrete {RoW}| treatment of waste reinforced concrete, collection for final disposal | APOS, U	Original	Rest of World (excl. RER)	1994	3	4	5	3	3
Waste treatment of untreated wood, burned onsite	Waste wood, untreated {GLO}| treatment of waste wood, untreated, open burning | APOS, U	Original	Global	2006	3	4	4	3	3
Waste treatment of untreated wood, buried onsite	Waste wood, untreated {GLO}| treatment of waste wood, untreated, unsanitary landfill, wet infiltration class (500mm) | APOS, U	Original	Global	2006	3	4	4	3	3
Waste treatment of treated wood, sanitary landfill	Waste wood, untreated {RoW}| treatment of, sanitary landfill | APOS, U	Original	Rest of World (excl. RER)	1994	3	4	5	3	3

	Full name of chosen unit process	Original/Adapted/ Created dataset	Geography	Time period of dataset	Pedigree matrix				
					Reliability	Completeness	Time-related	Geography	Technology
Waste treatment of steel components	Waste bulk iron, excluding reinforcement {RoW}| treatment of, sorting plant | APOS, U	Original	Rest of World (excl. RER)	1994	3	4	5	3	3
5. End of Life									
Road transportation by combination truck of waste	Transport, combination truck, diesel powered/US	Original	US	2010	2	4	4	3	2
Waste treatment of concrete	Waste reinforced concrete {RoW}| treatment of waste reinforced concrete, collection for final disposal | APOS, U	Original	Rest of World (excl. RER)	1994	3	4	5	3	3
Waste treatment of untreated wood, burned onsite	Waste wood, untreated {GLO}| treatment of waste wood, untreated, open burning | APOS, U	Original	Global	2006	3	4	4	3	3
Waste treatment of untreated wood, buried onsite	Waste wood, untreated {GLO}| treatment of waste wood, untreated, unsanitary landfill, wet infiltration class (500mm) | APOS, U	Original	Global	2006	3	4	4	3	3
Waste treatment of treated wood, sanitary landfill	Waste wood, untreated {RoW}| treatment of, sanitary landfill | APOS, U	Original	Rest of World (excl. RER)	1994	3	4	5	3	3
Waste treatment of steel components	Waste bulk iron, excluding reinforcement {RoW}| treatment of, sorting plant | APOS, U	Original	Rest of World (excl. RER)	1994	3	4	5	3	3
Waste treatment of elastomers	Waste plastic, mixture {RoW}| treatment of waste plastic, mixture, sanitary landfill | APOS, U	Original	Rest of World (excl. CH)	1994	3	4	5	3	3

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