Titre: Title:	Economic and environmental life cycle assessment of a short-span aluminium composite bridge deck in Canada
Auteurs: Authors:	Julien Pedneault, Victor Desjardins, Manuele Margni, David Conciatori, Mario Fafard, & Luca Sorelli
Date:	2021
Type:	Article de revue / Article
Référence: Citation:	Pedneault, J., Desjardins, V., Margni, M., Conciatori, D., Fafard, M., & Sorelli, L. (2021). Economic and environmental life cycle assessment of a short-span aluminium composite bridge deck in Canada. Journal of Cleaner Production, 310, 127405. https://doi.org/10.1016/j.jclepro.2021.127405

Economic and environmental life cycle assessment of a short-span aluminium composite bridge deck in Canada

AUTHORS

Julien Pedneault* (corresponding author) - CIRAIG, Mathematical and Industrial Engineering department, Polytechnique Montreal

3333 Queen Mary Rd suite 310, Montreal, Quebec H3V 1A2

Victor Desjardins - Centre d'expertise sur l'aluminium, The Quebec Aluminium industrial cluster

625, avenue du Président-Kennedy, bureau 505, Montréal (Québec) H3A 1K2

Manuele Margni - CIRAIG, Mathematical and Industrial Engineering department, Polytechnique Montreal - 3333 Queen Mary Rd suite 310, Montreal, Quebec H3V 1A2 ;

School of Engineering, University of Applied Sciences and Arts Western Switzerland (HES-SO), Sion, Switzerland

David Conciatori - CRIB, Civil and Water Engineering, Université Laval

1065, avenue de la Médecine - Pavillon Adrien-Pouliot, local 2928, Québec (Québec) G1V 0A6

Mario Fafard - Centre d'expertise sur l'aluminium, The Quebec Aluminium industrial cluster

625, avenue du Président-Kennedy, bureau 505, Montréal (Québec) H3A 1K2

Luca Sorelli - CRIB, Civil and Water Engineering, Université Laval

1065, avenue de la Médecine - Pavillon Adrien-Pouliot, local 2928, Québec (Québec) G1V 0A6

JOURNAL

Journal of cleaner production

ABSTRACT

The costs to maintain Québec's infrastructure—most of which was built in the 1960s and 1970s—are considerable, and major maintenance and reconstruction will be required in the coming years. In recent years, aluminum associations promote the increase of aluminum use in infrastructure and especially in bridge construction. This research aims to investigate the advantages of using aluminum deck bridges, which require less maintenance than traditional materials due to the natural resistance to atmospheric corrosion of aluminum, despite their higher investment costs that may limit their deployment. More specifically, the study compares for the first time the life cycle costs and environmental impacts of an aluminum-steel composite deck with a more traditional concrete-steel composite deck and provides a parametrized model allowing practitioners and designers to perform screening life cycle assessment and cost of short span bridge based on our data and results. Results show that the initial cost of aluminum deck is double that of concrete deck, but the overall cost is actually four times lower over the entire life cycle. The environmental results demonstrate the benefits of aluminum deck. Our main recommendation for future decision making in road infrastructure management is therefore to systematically expand the scope of the analysis integrating a full life cycle thinking also including the effects from traffic diversion.

KEY WORDS

Life-cycle cost analysis, life cycle assessment, bridge deck, aluminum-steel composite bridges, steel-concrete composite bridges.

WORLDCOUNT

7863

1 INTRODUCTION

A large share of Québec's infrastructure system was built in the 1960s and 1970. After half a century, the costs to maintain and repair it are increasing considerably. For instance, the road network in Québec, Canada includes over 9 600 structures and bridges at least 4.5 m long, and 67% of these bridges were built between the 1960s and the 1980s (Ministère des Transports du Québec, 2018). Major repairs are usually required 30 years after construction meaning that the actual need for maintenance work is therefore significant (Ministère des Transports du Québec, 2018). In this context, from a long-term perspective, it becomes of critical importance to compare the potential benefits of adopting more sustainable materials for the next generation of infrastructure.

In recent years, aluminum associations promote the increase of aluminum use in infrastructure and especially in bridge construction (IAI, 2018; European Aluminium, 2019; AAC, 2020; The Aluminum Association, 2020). Aluminum has potentially several properties that make it desirable for bridge applications, such as high resistance to weight ratio, good resilience to low temperatures (Viami International Inc. and The Technology Strategies Group, 2013) and durability due to its natural resistance to atmospheric corrosion (Vargel, 2002). Current research and design have made aluminum decking an alternative to the usual reinforced concrete slab, which has been used for decades to build and restore dozens of bridges in Europe and North America (Siwowski, 2006). Aluminum's advantageous properties suggest that aluminum decking would require less maintenance as compared to traditional designs, and lightweight aluminum deck is easier to transport and install but the initial cost of aluminum decking limits its deployment. According to estimates by Burgelin (2017a), the initial cost of aluminum decking is 2.6 times greater than an equivalent concrete decking.

In order to evaluate the relevancy of aluminium as a construction material in bridge, a life cycle thinking is needed to avoid any potential shifting of the environmental burden to other life cycle phases or impact categories (Mermer, 2012). In a bridge management perspective, accounting for the full life cycle is highly relevant because some design options, despite higher initial costs and greater material-related environmental impacts on a per mass basis, result in lower life cycle costs and reduced environmental impacts when evaluated over their entire life cycle (Kendall, Keoleian and Helfand, 2008; Kripka, Yepes and Milani, 2019). Life cycle cost analysis (LCC) and life cycle assessment (LCA) are both tools based on life cycle thinking and could help the evaluation the performance of aluminium in bridge construction.

Previous LCA on bridges have shown that environmental life cycle profile sometimes shows different conclusions across impact categories, substantiating the importance of including as many environmental impact categories to avoid problem shifting (Hammervold, Reenaas and Brattebø, 2013). For this reason, global warming alone cannot necessarily comprehensively represent the environmental profile of a bridge (Laurent, Olsen and Hauschild, 2012) and the choice of the impact indicators is critical in representing the environmental performance of a bridge (Du, Pettersson and Karoumi, 2018). Studies combining LCC and LCA have shown that best economic option may be different from the optimal environmental choice (Gervásio and da Silva, 2008; Pang *et al.*, 2015; Kripka, Yepes and Milani, 2019). Concerning the social pillar of the sustainability, it seems to have a high interrelation between the environmental and social impact indicators for each life cycle stage of a bridge (Penadés-Plà *et al.*, 2020).

Generally, a product system that has a longer life span and requires less maintenance tends to have a lower life cycle cost and low environmental impacts (Itoh and Kitagawa, 2003; Mara *et al.*, 2011). However, it is impossible to make a general statement about which material provides the best option for bridge design. Materials that provide the best environmental solution in one project do not necessarily perform better in another context because every construction project is different (Daniel, 2003). Thus, life cycle analyses must always be contextualized.

To the best of our knowledge, there has not been studies evaluating both the cost and environmental impact of aluminum decking for road transport from a life cycle perspective. The goal of this project aims to fill this gap by comparing two different short-span bridge designs adapted for a rural region in Canada: a composite aluminum deck on steel beams (AD) and a concrete deck on steel beams (CD) using LCA and LCC. The comparison between an innovative aluminum deck with a more traditional composite steel-concrete bridge is suitable because it is the most common type of short span bridge deck in Québec. In recent years, MTQ has promoted composite steel-concrete design for replacement of concrete bridge.

A life cycle cost and environmental profile of the two bridge designs were first performed to identify hotspots and key parameters of each system. Environmental and cost results were then aggregated through the monetarization of environmental externalities. The effects of aluminum sourcing and traffic deviation and volume were also analyzed through a sensitivity analysis.

2 MATERIALS AND METHODS

2.1 GENERAL FRAMEWORK AND SCOPE OF STUDY

Two general frameworks were used in the study: the ISO 15686-5 standard (2017) for the LCC, and the ISO 14040 standard (2006) for the LCA. A common scope (function, functional unit and system boundaries) was developed to ensure consistent integration between the LCC and LCA, despite a few methodological differences between the two approaches.

The function of the product system is to ensure the continuity of road transport between two roads over an obstacle. This leads to the following functional unit: *ensure normal traffic on two lanes over an obstacle over a distance of 20 metres for 75 years*. A service life of 75 years has been chosen because it corresponds to minimum lifespan of a bridge prescribed by the Canadian Highway Bridge Design Code (SCC, 2014).

The product system fulfilling the functional unit includes unit processes and their respective elementary and product flows throughout the entire life cycle (ISO, 2006). The abutments of the bridge are excluded from the product system because they are considered identical between both systems. We subdivided the product system into three different scopes of analysis as shown in Figure 1. The first scope encompasses the initial construction. The second scope includes the first and additionally includes all maintenance and end of life-related processes. The third scope expands on the second one by including the effects of the traffic diversion caused by the maintenance work. The aim of separating the product system into three different boundaries is to develop a better understanding of the life cycle impacts and identify potential trade-offs.

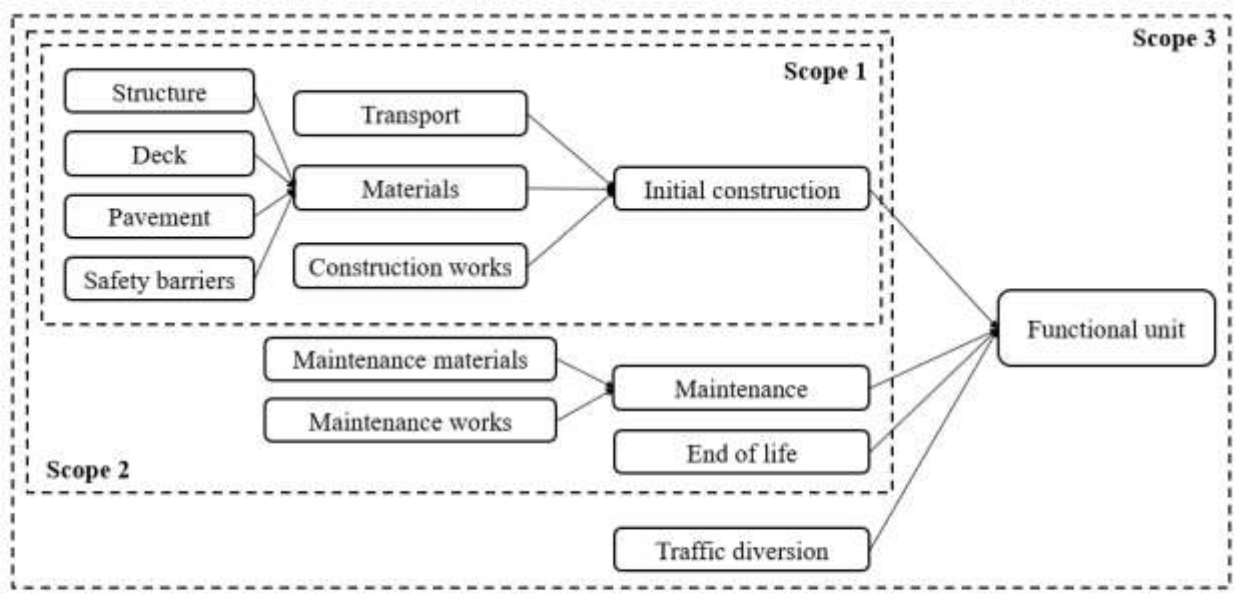


Figure 1: Representation of product system with three different boundaries

Regarding traffic diversion, parameters referred to a specific context were used: a bridge located in the municipality Lac-Brome, Québec, Canada with an annual average daily traffic flow (AADT) of 2 500 vehicles, of which 7% are trucks with an average load of 9.5 t. The length of the traffic diversion is 25 km, with vehicles travelling at an average speed of 50 km/h. An annual 1% increase in AADT was assumed.

We also assumed that metals, steel and aluminum are recycled at the end of the bridge's life, while other construction materials are sent directly to landfill. The multifunctionality problem of recycling materials in LCA is addressed by system expansion using the end-of-life recycling approach.

For the LCC, the end of life stage was excluded from the system boundaries because they are similar for the two bridges decks and because they contribute less than 1% of the total life cycle cost (Eamon *et al.*, 2012; Pang *et al.*, 2015).

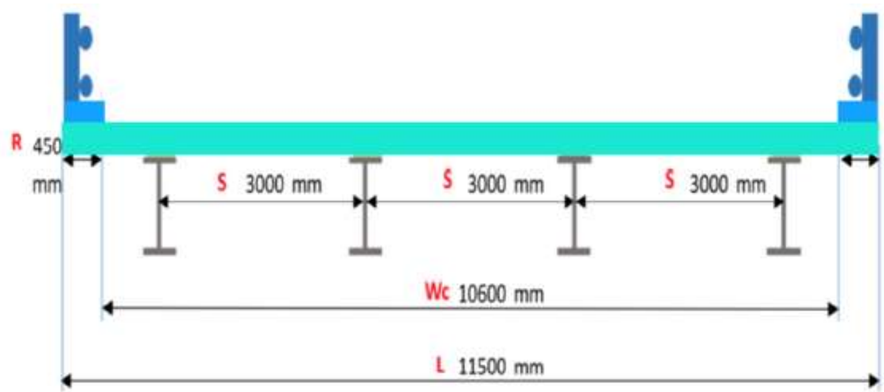
2.2 BRIDGE DECK DESIGN

The superstructures were designed according to the standards of the Canadian Highway Bridge Design Code CSA S6-14 (SCC, 2014) using the simplified method of analysis for longitudinal stresses. We designed a mixed steel/concrete deck using studs welded to the steel flange to connect the two materials (a single neutral axis) while the geometry of the aluminum decking was provided by a related research project (Djedid *et al.*, 2019).

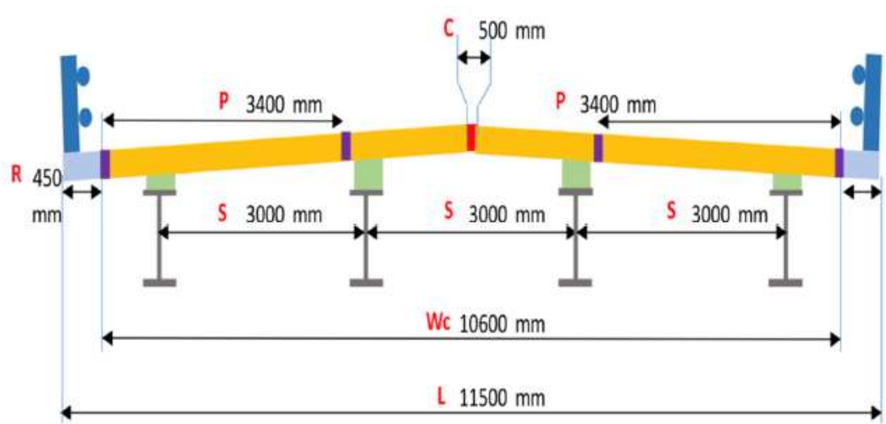
The design phase was carried out to determine the quantities of materials used for each of the bridges in the study. The design of the girders for the aluminum deck bridges met the standard's values of truck load fractions. In fact, under the standard, the values of the truck load fractions for an aluminum deck are the same as those used for a wooden deck, despite evidence that an aluminum deck offers better transverse stiffness than a wooden one. The cautious approach taken by the standard is likely a result of the lack of solid evidence on aluminum at the time the project was carried out. Since then, research has shown that the values to be used are similar to, or even lower than, those calculated for a concrete slab bridge (Burgelin, 2017b; St-Gelais, 2018). From these revised values, we obtained similar steel sections for the aluminum and concrete decks.

The stress calculation was estimated using finite element analysis with a high mesh density. Thus, the resistance to fatigue has been carefully considered following requirements from section 17.20, focusing on fatigue design, of the Canadian Highway Bridge Design Code CSA S6-14 (SCC, 2014).

Figure 2 shows the cross-section and overall dimensions of each bridge deck design. With a total distance length of 21.8m and a total width of 11.5m, both bridge decks have an area of 250.7 m^2.



a)



b)

Figure 2: Section details and main dimensions of bridge deck design: a) concrete-steel composite bridge and b) aluminum-steel composite bridge

2.3 DEFINITION OF MAINTENANCE SCENARIOS

Maintenance scenarios were defined for the two bridge decks (i.e., the nature, frequency and duration of maintenance operations) in order to identify all costs over the life cycle. All routine maintenance operations (i.e., inspection, cleaning, etc.) are the same regardless of the bridge type and therefore excluded from the study. The same assumption applies to the demolition costs. Maintenance scenarios are described in

Table 1. Scenarios were established in discussions with committees of expert engineers from the Ministère des Transports du Québec (MTQ) to obtain a consensus on the nature, frequency and duration of maintenance operations. For aluminum, the scenario was established based on a literature analysis of the durability of aluminum bridges (Mader and Pieper, 2006; Siwowski, 2006; Beaulieu, Internoscia and Hartileb, 2015; Freeman and Potter, 2017).

Table 1: Maintenance scenarios for concrete and aluminum decks

	Maintenance work	**Frequency [years]**	**Requires bridge closure**	**Length of work [days]**
Steel-Concrete deck	Concrete protection	10	No	-
	Pavement	12.5	Yes	2
	Pavement and deck repair	25	Yes	21
	Replacement of the concrete slab	50	Yes	55
	Painting of steel structure	50	No	-
Aluminum deck	Pavement	25	Yes	1
	Bolt replacement under the deck	25	No	-
	Bolt replacement	50	Yes	5

Steel-Concrete decks generally require more maintenance work compared to aluminum decks due to the lower durability of concrete decks; such decks are particularly vulnerable to corrosion damage when exposed to de-icing salts. The maintenance works contribute to extend the service life of the structure to the 75 years prescribed by the code. Aluminum has a higher corrosion resistance leading to a reduced need for maintenance work.

2.4 LIFE CYCLE COST ANALYSIS

2.4.1 Cost calculation

Following our 3 scopes previously defined, the cost has been divided into initial costs, maintenance costs and costs caused by traffic diversion during construction and the maintenance activities. To ensure comparability between the costs incurred in different years over the life cycle, the net present value of future costs must be determined. In doing so, we acknowledge that money available at the present time is worth more than the identical sum in the future. We apply the net present value method to convert all future economic flows into the year of construction of the structure by applying a discount rate, as per equation (1). This rate thus acts as a conversion rate between the future and present.

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \qquad (1)$$

where NPV: net present value; r: discount rate; t: year considered and C_t : sum of all cash flows in year t.

For this study, the life cycle cost is therefore the sum of the three types of cost converted into NPV as per equation (2).

$$LCC = C_c + \sum_{i=1}^{N} \frac{C_{m_i}(t_i)}{(1+r)^{t_i}} + \sum_{i=1}^{N} \frac{C_{road\ closure,m_i}(t_i)}{(1+r)^{t_i}} \tag{2}$$

With:

- LCC, life cycle cost
- C_c, initial construction cost
- $C_{m_i}(t_i)$, maintenance cost in year i
- r, discount rate
- t_i, year considered
- $C_{road\ closure,m_i}(t_i)$, road closure cost associated with maintenance in year i.

The choice of discount rate is likely to have a significant impact on investments in the industrial sector. This is especially the case for projects that are part of a sustainable development approach, such as this research project. Indeed, the aim of discounting is to reduce the significance of the future cost: the further the cost horizon, the smaller the future cost will be. While the issue of what constitutes an appropriate discount rate value is much debated in the economics community (Gollier, 2013), there is a consensus that a discount rate that is too high introduces a bias that favours a short-term view, since it would erase the importance of future costs by reducing them to almost zero in the long term and ultimately negate the value of an LCC.

In the context of a public sector investment, Moore et al. (2004) distinguish two types of projects: intragenerational (T < 50 years) and intergenerational (T > 50 years). With a functional unit of 75 years, the bridge is considered an intergenerational project, and the suggested range of discount rate is between 0 and 3.5 percent (Moore *et al.*, 2004). Following discussion with the MTQ, a discount rate of 2.37% was selected. A sensitivity analysis with variations of ± 0.5% and 1% was conducted to test the impact of this arbitrary choice of discount rate on the LCC results.

2.4.2 Costs description and data collection

Initial costs and maintenance costs are both direct costs that affect the owner of the structure. On the other hand, cost caused by traffic diversion are indirect costs borne by users of the bridge. Scope 1 and scope 2 of the analysis only take the direct cost in consideration while a mix of direct and indirect costs is made with the scope 3.

Data collection for the direct costs are determined through an inventory of the construction and maintenance costs paid by the MTQ for all the projects undertaken each year, which includes unit costs for every operation (e.g., resurfacing costs per unit area of surface, concrete pouring costs per unit of volume poured, etc.). These unit costs are calculated based on the nature of the work, maintenance scenarios, unit values of the various works and unit values of indirect costs.

The cost of traffic diversion was calculated based on the user delay cost (i.e., time wasted in traffic diversions), the operating costs attributable to additional fuel consumption and the additional cost related to vehicle depreciation.

User delay costs are determined at a specific time as per equation (3)

$$\left(L_{detour} - L_{bridge}\right) \times 2 \times AADT \times (1+h)^{(t_i - 2018)} \times N \times \alpha \qquad (3)$$

with

- $L_{detour,}$ the length of the detour when the bridge is closed due to construction or maintenance
- $L_{bridge,}$ the length of the bridge
- AADT, the annual average daily traffic per lane, differentiated according to the vehicle type (vehicle flow rate and truck flow rate)
- h, the growth rate of the AADT
- t_i, the year of the operation
- N, the number of days of road closure
- α, user delay cost per kilometer based on an average occupation rate of 1.23 (MTMDET, 2016)

Operating costs (fuel consumption) are calculated as per equation (*4*).

$$\left(L_{detour}. - L_{bridge}\right) \times 2 \times \text{AADT} \times (1+h)^{(t_i - 2018)} \times N \times \beta\ , \qquad (4)$$

where β is the cost of fuel in \$/km for a specific speed.

Operating costs (vehicle depreciation) are calculated as per equation (*5*),

$$\left(L_{detour} - L_{bridge}\right) \times 2 \times AADT \times (1+h)^{(t_i - 2018)} \times N \times \gamma\ , \qquad (5)$$

where γ is the distance-based cost for depreciation, maintenance and tires in \$/km.

All parameters (unit cost data) required to assess these costs are taken from the MTQ's cost-benefit guide (MTMDET, 2016) while they are the most appropriate data for Quebec, the region where the bridges are evaluated. The data used to calculate the LCC associated to a speed of 50 km/h are grouped in Table 2.

Table 2: Cost per kilometer of extra distance caused by traffic diversion with an average speed of 50 km/h. Total cost is the sum of fuel cost, maintenance cost and time wasted.

		Car	Truck
L_{detour}	Length of the detour [km]	25 km	
L_{bridge}	Length of the bridge [m]	20 m	
AADT	annual average daily traffic per lane [u / day]	2325	175
h	the growth rate of the AADT	1 %	
α	user delay cost per kilometer [$ / km]	0.322	0.9716
β	cost of fuel [$ / km]	0.171	0.412
γ	cost for depreciation, maintenance and tires [$ / km]	0.110	0.210

2.5 Life cycle assessment

2.5.1 Inventory

The foreground data of the study (i.e., the quantification of the main flows needed to complete the functional unit) were developed based on the design of the deck, expert opinions from the MTQ and historical data. The main foreground flows and their quantities are presented in Table 3. The pavement of the aluminum deck is made with Bimagrip LS®, a three-component polyurethane system, which, when combined with an aggregate, creates a high friction, anti-skid surface on the deck bridge (VinMar, 2019).

Table 3: Main flows and quantities for every scope of the CD and AD systems

				Quantity						
				Flow	CD	AD	Units	CD	AD	Units
Scope 3	Scope 2	Scope 1	Structure	Steel	2.28E+04	1.93E+04	kg	90.95	76.98	kg/m²
			Deck	Aluminum	-	2.40E+04	kg	-	95.73	kg/m²
				concrete, 35 MPa	5.11E+01	-	m^3	0.20	-	m^3/m^2
				Steel	1.15E+04	2.77E+02	kg	45.87	1.10	kg/m²
			Pavement	Bitumen	3.68E+04	-	kg	146.79	-	kg/m²
				Bimagrip LS®	-	3.17E+03	kg	-	12.64	kg/m²
		Maintenance		Bitumen	1.84E+05	-	kg	733.94	-	kg/m²
				Bimagrip LS®	-	6.34E+03	kg	-	25.29	kg/m²
				Concrete, 35 MPa	6.64E+01	-	m^3	0.26	-	m^3/m^2
				Steel	1.60E+04	5.11E+02	kg	63.82	2.04	kg/m²
		End of life		Recycling scrap steel	5.48E+03	2.21E+04	kg	21.86	88.15	kg/m²
				Recycling aluminum	-	2.16E+04	kg	-	86.16	kg/m²
				Inert waste	5.02E+05	9.51E+03	kg	2002.39	37.93	kg/m²
	Traffic diversion			Transport, passenger car	1.47E+07	1.11E+06	km	58635.82	4427.60	km/m²
				Transport, freight, lorry	1.05E+07	7.90E+05	tkm	41882.73	3151.18	tkm/m²

A more detailed and complete list of flows for both systems is included in the supplementary information (SI).

The background data used to model the cradle-to-gate life cycle inventory are from the *ecoinvent* 3.3 cut-off version environmental database (Wernet *et al.*, 2016).

2.5.2 Impact assessment

The Impact2002+ (Jolliet *et al.*, 2003) impact assessment method was used to calculate life cycle impacts in 14 midpoint categories and 4 damage categories: climate change (CC) with kg CO_2 eq as unit, ecosystem quality (EQ) with pdf*m^2*year as unit, human health (HH) with disability-adjusted life year (DALY) as unit and resources (R) with MJ as unit. The LCA calculations were performed using openLCA 1.7.4 (https://openlca.org).

2.5.3 Interpretation

The LCA results are interpreted through contribution analyses for each scope. Sensitivity analyses were also conducted to test the effects of certain assumptions. In order to identify and prioritize the sensitivity analysis, we first evaluated the data quality of inputs of the LCA model and we then performed a contribution analysis to identify the most contributing parameters on the results. Finally, we identified the most sensitive parameters to undergo the sensitivity analysis based on the quality of input data and the contribution analysis. The data quality evaluation, based on a pedigree matrix (Weidema and Wesnæs, 1996), is available in the last columns of the two tables in SI. As an outcome of this prioritization process we identified the need to perform a sensitive analysis on the following parameters/scenarios: the traffic diversion, the discount rate, the origin of the aluminum, the exclusion of the impacts from the bridge abutments and the selection of impact assessment method.

An uncertainty analysis was also conducted on the LCA results. A Monte Carlo simulation with a thousand iterations was carried out on the subtraction of the AD system from the CD system to ensure the consideration of dependencies between the parameters common in both systems. A negative value indicates that the impact of AD is higher than that of CD. A normal distribution for all data and parameters was used, except for recycling yield, which was modeled by a triangle distribution to avoid impossible values for yield. Three levels of variability were used to estimate uncertainties. Each level was associated with a coefficient of variation: low (2.5%), average (12.5%) and high (25%).

2.6 MONETARIZATION

Monetarization is the practice of converting measures of social and biophysical impacts into monetary units and is used to determine the economic value of non-market goods (i.e., goods for which no market exists) (Pizzol *et al.*, 2015). It makes it possible to compare environmental impact and life cycle cost.

The StepWise2006 method (Weidema, 2009) was used based on a budget constraint approach. Because the method uses the Euro currency unit at its average value in year 2003, we converted it into Canadian dollars with the average exchange rate from 2003: 1.58 (Government of Canada, 2005). A conversion of impact categories was required because the method uses quality-adjusted life year (QALY) to represent human health (1 QALY= −1 DALY) and biodiversity adjusted hectare years (BAHY) for ecosystem quality (1 BAHY=−10,000 PDF m^2 years). No conversion was needed for climate change (kg CO_2 eq).

3 RESULTS

3.1 LIFE CYCLE COST AND ENVIRONMENTAL PROFILE AND CONTRIBUTION ANALYSIS

The presentation of the environmental and cost results based on our deck design, maintenance scenarios and traffic assumption are structured according to the three scopes of the analysis. In order to evaluate the repercussions arising from the choice of scope on the LCA and LCC, a contribution analysis for each scope is presented.

The results of the contribution analysis of Scope 1 (bridge construction) are shown in Figure 3. The concrete deck represents 47% of the cost of the aluminum bridge deck. The deck's aluminum cost is responsible for over 50% of the overall construction cost. The steel beam structure is also a relevant contributor to the total costs of both bridges, contributing to 52% and 33% of the CD and AD, respectively. The pavement and safety barriers represent a relative contribution of less than 10% of the total costs for both options.

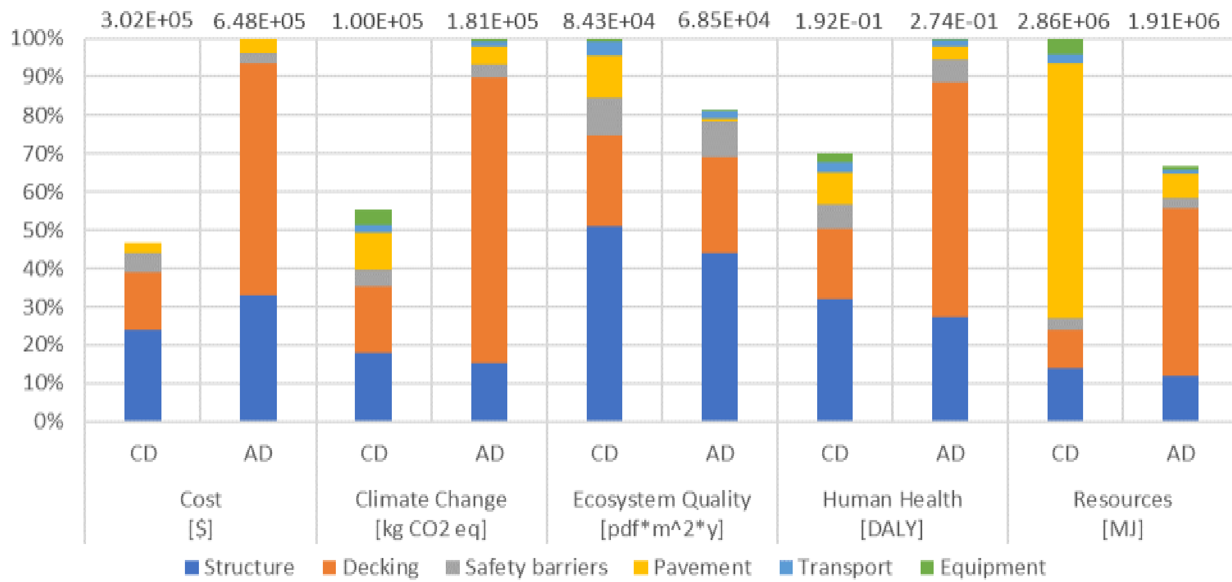


Figure 3: Comparison of LCC and LCA relative results according to the scope 1 comprising all processes needed for the initial construction. CD represents the concrete decking on the steel beam system and AD represent the aluminum decking on the steel beam system.

Scope 1 results show that the aluminum bridge deck performs better than the concrete bridge deck for the EQ and R indicators. The two other environmental indicators (CC and HH) favour the CD. Like the cost contribution, aluminum and steel production are responsible for most of the environmental impacts, while material transport and construction activities have a limited relative contribution. For the resource indicators, the pavement of the concrete bridge is responsible for 65% of the total potential impacts. This is explained by the use of pitch derived from petrol for the manufacturing of bitumen adhesive. Results of the Scope 2 (construction + maintenance + end-of-life, excluding traffic diversions) are shown in Figure 4. Materials maintenance accounts for additional materials to ensure the operation of the bridge throughout its entire life cycle. The maintenance work includes work activities and the transport of the material throughout the entire life cycle. Negative results represent the avoided impacts of new virgin materials, which are displaced using recycled materials. The end-of-life stage includes the activities for the end-of-life management of all the materials generated during the bridge's life cycle.

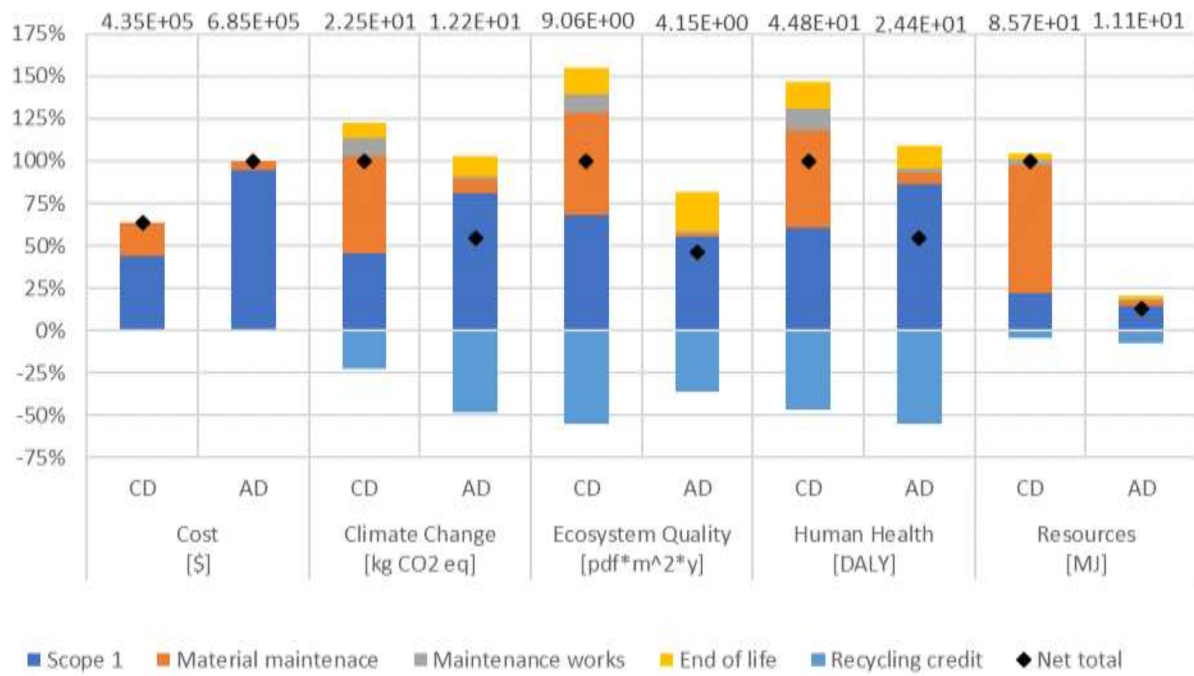


Figure 4: Comparison of LCC and LCA relative results according to the scope 2, which is the sum of the initial construction, maintenance materials and works needed to ensure the operation of the bridge throughout its entire life cycle and the end of life processes. CD represents the concrete decking on the steel beam system and AD represent the aluminum decking on the steel beam system.

The life cycle costs of the concrete deck for Scope 2 are still lower than those of the aluminum deck by 37%, despite the fact that the aluminum deck requires less material for the maintenance activities. The cost of Scope 1 represents the biggest share of life cycle costs for both systems. The discount rate applied on the future economic flows related to maintenance explain why the initial cost still dominates.

All the environmental impact categories are in favor of the aluminum bridge deck. The total potential impact of the aluminum deck is 84% for CC, 53% for EQ, 74% for HH and 20% for R as compared to the concrete deck by normalizing with the total amount of potential impact excluding the credits. The environmental credit from recycling steel and aluminum and using these to displace virgin material may reduce the environmental impact scores by as much as 40%. Once again, the maintenance activities contribute little to the total impacts.

A comparison of the results for Scope 3, which include traffic diversion due to maintenance activities as well as construction, maintenance and end-of-life, is shown in Figure 5.

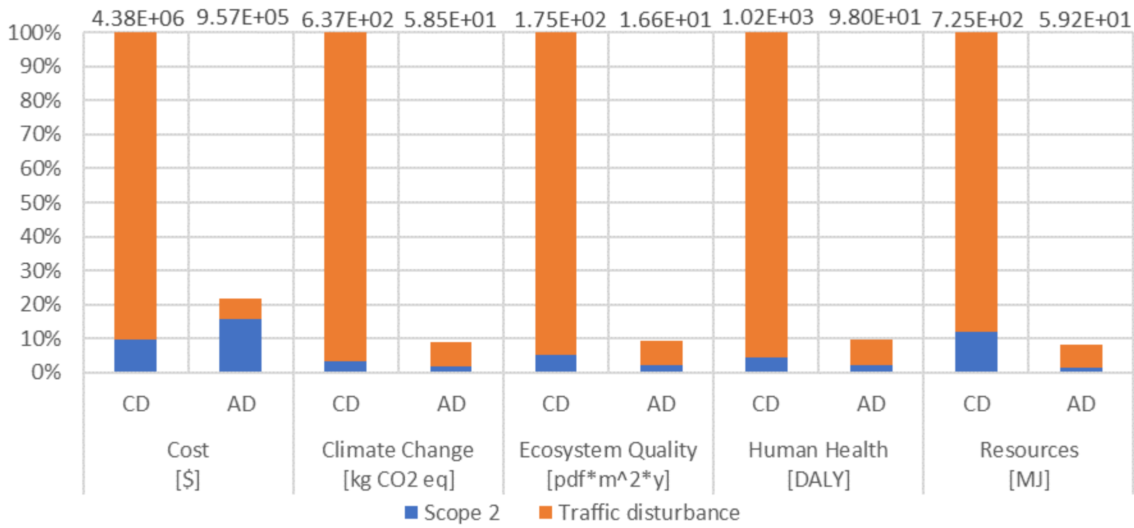


Figure 5: Comparison of LCC and LCA relative results according to the scope 3. The functional unit of both systems is to ensure a normal traffic on two lanes above an obstacle with a span of 20 meters for 75 years. CD represents the concrete decking on the steel beam system and AD represent the aluminum decking on steel beam system.

With the specific AADT and length of detours used (2 500 vehicles with a 7% proportion of trucks diverted over 25 km at a speed of 50 km/h), traffic diversion are responsible for over 90% of each indicator and consequently, changes the overall conclusion of the LCC; with the AD becoming the better option. The concrete bridge deck becomes five times more expensive than the aluminum bridge deck, highlighting the importance of accounting beyond the initial cost and adopting life cycle thinking. The Scope 3 LCA results confirm that the aluminum deck remains the preferred option in terms of all environmental indicators while increasing the difference between the two deck options as compared to Scope 2. The results for the three scopes are shown on the tornado diagram in Figure 6. They are normalized by the results for the concrete bridge deck (black horizontal line). The initial construction cost (scope 1) of the aluminum bridge deck is more expensive and has higher environmental impacts in the climate change and human health categories. By considering the costs throughout the life cycle and potential impacts including maintenance, end-of-life and traffic diversion, the aluminum bridge is the preferred design option of the two studied.

Initial construction of aluminum decking is four times more expensive than CD decking because aluminum is more expensive than reinforced concrete. On the other hand, the maintenance activities of AD are 3.5 times lower than for the CD. However, the main cost difference between the two designs lies in the indirect cost. There is a factor 14 between the costs of traffic diversion due to shorter maintenance periods for AD.

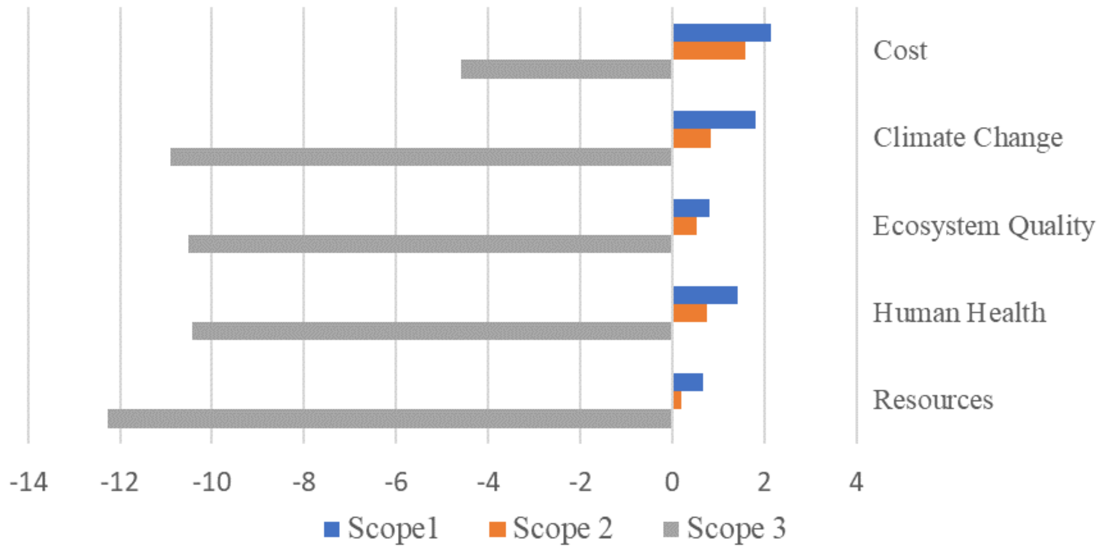


Figure 6: AC results normalised by CD results for every scope. When the bar is on the positive side, it shows how many times AC is higher than CD. When the bar is on the negative side, it shows how many times AC is lower than CD. For example, for scope 1 (initial construction only), AC is two times more expensive than DC, but, for scope 3 (full life cycle and traffic diversion), it is five times less expensive.

To sum up previous figures, Table 4 shows the results of the LCC and the climate change indicator of the LCA in absolute and relative (by m^2) of the two bridge decks.

Table 4: Absolute and relative (/m^2) cost results and climate change results according different scopes for concrete bridge (CD) and aluminum bridge (AD)

				Total cost [10^3 $]		CC [10^5 kg CO_2 eq]		Cost [$ / m^2]		CC [10^3 kg CO_2 eq /m^2]	
				CD	AD	CD	AD	CD	AD	CD	AD
Scope 3	Scope 2	Scope 1	Structure	156	212.9	3.28	2.80	622	849	13.1	11.2
			Decking	97.3	391.8	3.20	13.62	388	1,563	12.8	54.3
			Safety barriers	31.8	17.5	0.79	0.63	127	70	3.2	2.5
			Pavement	16.7	25.4	1.74	0.83	67	101	6.9	3.3
			Transport	-	-	0.40	0.22	-	-	1.6	0.9
			Construction	-	-	0.74	0.18	-	-	3.0	0.7
			Total Scope 1	**301.8**	**647.6**	**10.1**	**18.3**	**582**	**2 583**	**40.5**	**72.9**
		Maintenance activities		133.4	37.7	12.3	-6.05	532	150	49.1	-24.1
		Total scope 2		**435.2**	**685.3**	**22.5**	**12.2**	**1 114**	**2 734**	**89.6**	**48.7**
	Traffic diversion			3 948.0	272.0	819.6	95.0	1 646	2 884	3 269.2	378.9
	Total scope 3			**4 383.2**	**957.3**	**842.0**	**107.2**	**2 759**	**5 617**	**3 358.8**	**427.7**

Finally, the monetarization of the environmental impacts was performed by applying the StepWise2006 method (Weidema, 2009) to aggregate the LCC and LCA results into a single score. The cost of environmental externalities was thus added to the private costs supported by all stakeholders throughout the bridge's life cycle (direct costs supported by the owner of the bridge, plus the direct and opportunity costs of the users). The resulting single scores represent the total societal cost associated with the two studied bridge decks. The monetarized environmental impacts added to the LCC result for scope 3 are shown in Figure 7 .

Figure 7: Comparison of LCC result and the monetarization of environmental impacts.

Environmental cost represents 40% and 27% of the total cost of the concrete and aluminum decks, respectively. Nevertheless, the conclusion of the comparison does not change with the integration of the environmental cost. The concrete decking remains the most expensive option, which is logical because it also has a greater environmental impact than the aluminum decking.

3.2 Sensitivity analysis

Based on the main contributor of the results, we conducted sensitivity analysis to deepen the interpretation of the results and their conclusion.

3.2.1 Traffic diversion

Traffic diversion are the greatest contributor to most of the life cycle cost and environmental impacts. A sensitivity analysis was therefore carried out on this key parameter. Although detour distances and AADT are specific to each bridge, to facilitate the interpretation of the results using a more universal perspective, traffic diversion was subdivided into units of traffic diversion. One unit corresponds to the total amount of traffic diversion in vehicle-kilometers (vkm) caused by maintenance activities over 75 years. Three parameters characterize the size of the unit: the number of days where maintenance activities required bridge closure, AADT and detour distance. While the first parameter is dependent on the design of the bridge, the latter two parameters depend on the location of the bridge, and their variability can be significant. The costs of one unit of an AADT of 2 500 and detour of 5 kilometers was calculated for each bridge and is also equivalent to an AADT of 1 000 and detour distance of 12.5 kilometers. By adding multiple units, it is possible to obtain the tipping point at which the aluminum deck becomes less expensive than the concrete option (Figure 8).

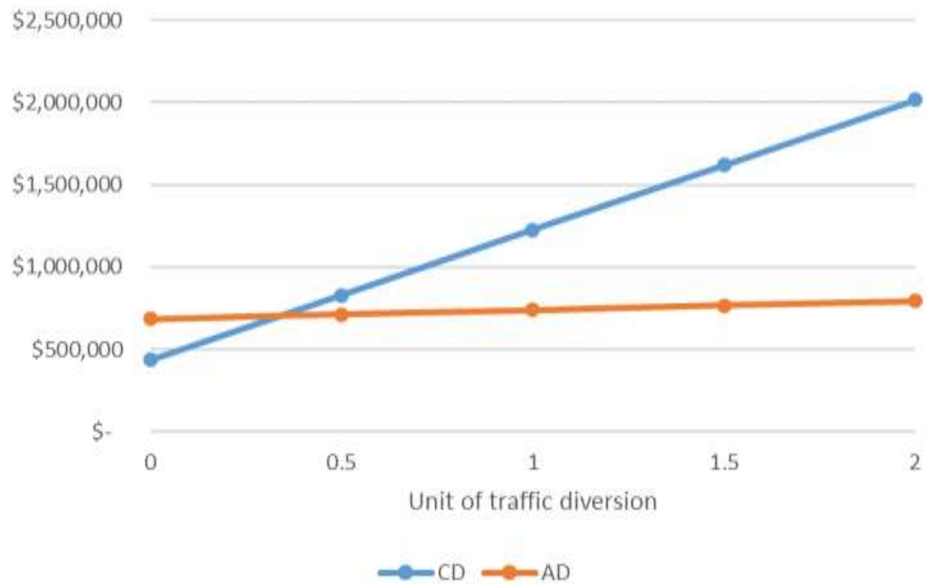


Figure 8: Evolution of LCC for different amounts of unit of traffic diversion of an AADT of 2 500 and a detour distance of 5 kilometers. The tipping point occurs at 0.32, meaning an AADT of 800 for a detour of 5 km or any other equal combination.

The tipping point occurs at 0.34 units, which is equivalent to an AADT of 800 for a 5-km detour. Note, however, that since the units are in vkm, a multitude of combinations of AADT and detour length are also equivalent.

Another important parameter in traffic costs and impacts quantification is the amount of truck traffic in the AADT. An average rate of 7% is used in the case study and in the definition of a unit of traffic diversion. The share of trucks can vary significantly depending on the specific situation. A bridge located close to an industrial park will have a much higher share of trucks than one near a residential neighbourhood. The proportion of the cost and environmental impact of trucks and cars was calculated (Figure 9). Even if truck traffic accounts for only 7% of traffic, it is responsible for 31% of the cost of traffic diversion and between 22 and 45% of the environmental impacts. This is explained by the fact that the economic cost of time wasted in a traffic diversion by a truck as part of a commercial activity is higher than that of a personal car (i.e., $13.52/h vs $23.63/h, respectively). There is also a difference in fuel consumption, maintenance costs, tire use, etc. A sensitivity analysis was carried out to study their influence on the results traffic diversion with a truck rate of 5% and 10% (Figure 9).

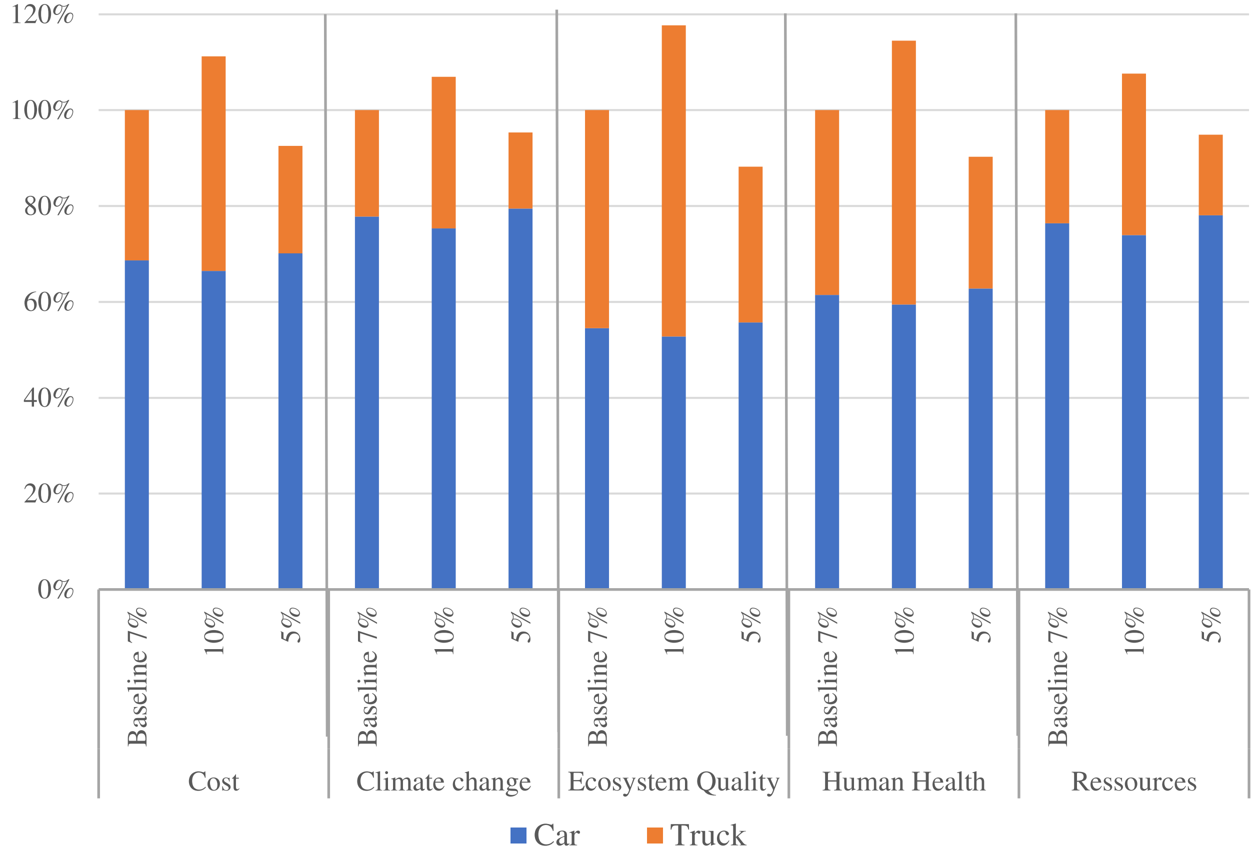


Figure 9: Sensitivity analysis on impacts and cost life cycle results from a varying composition of the diverted traffic Percentage values refers to share trucks in the traffic.

With an increase of proportion of 10% of truck instead of 7%, the cost of traffic diversion increases of 11% and environmental impacts from 7% to 18%. On the other hand, a truck rate of 5% would reduce cost of 7% and reduce environmental impacts between 5% and 12%.

3.2.2 Discount rate

As part of the sensitivity analysis of the discount rate, we tested a variation of ± 0.5 and 1 percentage points on the 2.37% discount rate in the case study. Figure 10 shows the results of the LCC for different discount rates.

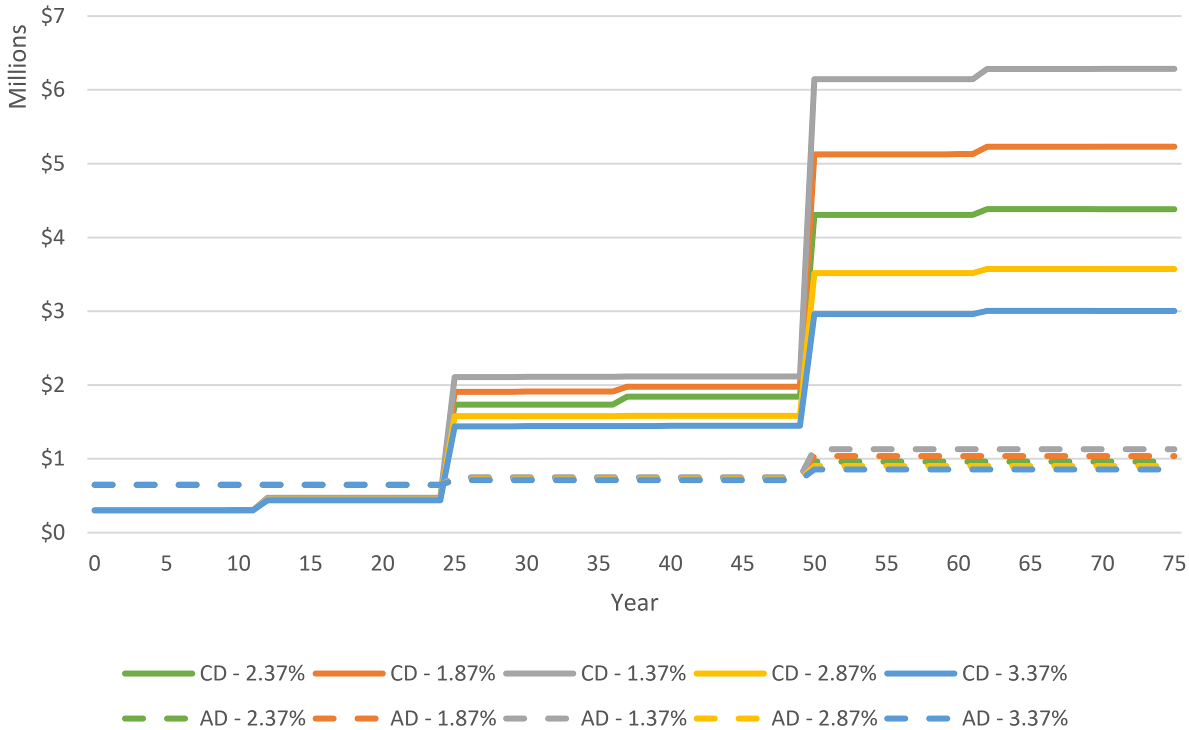


Figure 10: Sensitivity analysis of the discount rate used in the LCC. A variation of ± 0.5 and 1% shows the high sensitivity of the parameter but does not change the study conclusions. A lower discount rate increases the gap between the LCC results.

The variations in discount rate do not change the overall conclusions of the comparison. The aluminum bridge deck is still less expensive when looking at the entire life cycle, regardless of the discount rate. The life cycle cost difference between the two systems tends to decrease as the discount rate rises. This may be explained by the fact that the concrete deck requires more maintenance during its life cycle and a higher discount rate decreases the significance of future costs when converted into a net present value. Figure 11 shows the evolution of the difference in LCC results between concrete and aluminum deck. The findings are inverted with a discount rate of 10%, which is generally considered too high for a public sector investment. The sensitivity analysis shows that the conclusions remain the same within a realistic discount rate.

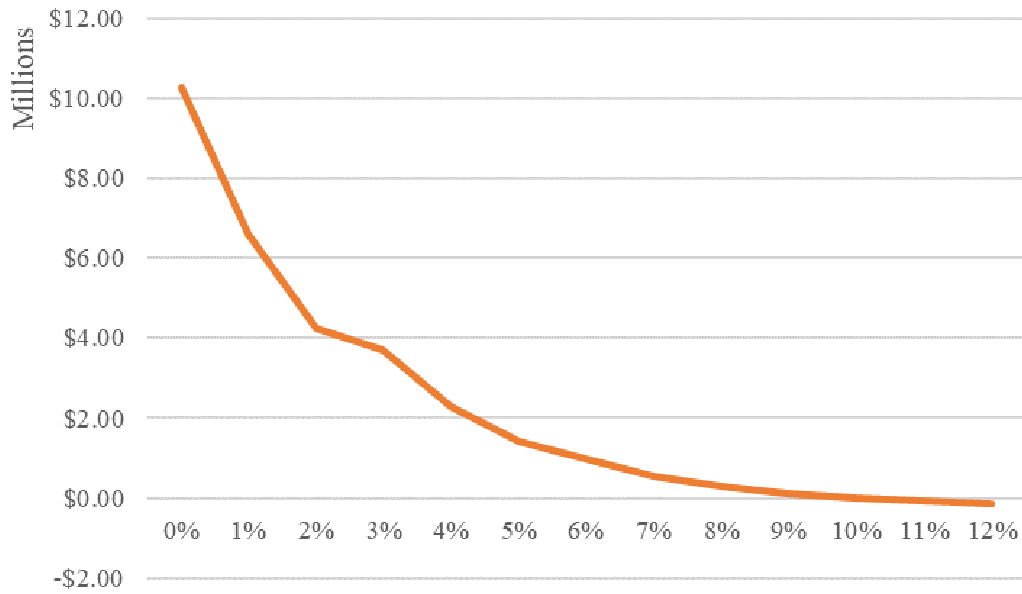


Figure 11: Difference between CD and AD LCA results based on different discount rates. AC becomes more expensive than CD with a discount rate of 10%.

3.2.3 Duration of the functional unit

In order to test the 75 years assumption of the FU, a sensitivity analysis presenting results of Scope 2 and Scope 3 with a 50-year and 100-year service life is presented in SI-3. The analysis shows that changing the temporal length of the FU would not change the overall conclusions of the comparison, although the relative difference between the two results would change (see SI-3 for results and additional discussion).

3.2.4 Aluminum provider

Seeing as aluminum production is energy intensive, the electricity mix used in its smelting is of great importance. Consequently, we evaluated the gains from sourcing it from Québec, where the electricity mix is 100% hydropower as opposed to sourcing aluminum from USA where the electricity mix is 49% fossil-based. An alternative scenario in which the aluminum is sourced from USA was been added in Figure 12.

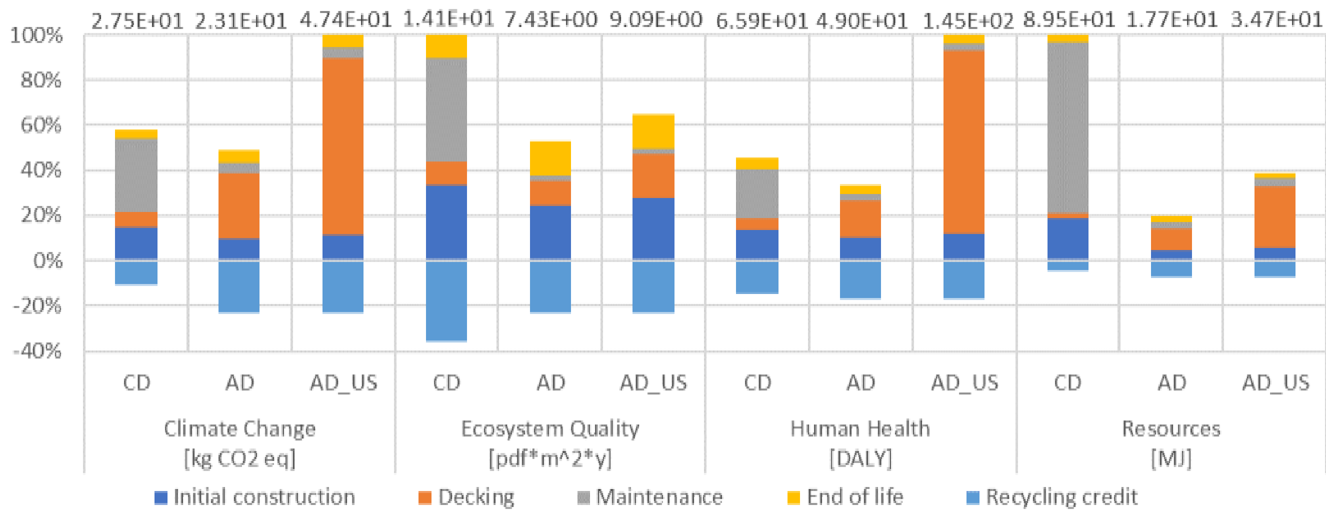


Figure 12: Sensitivity analysis of aluminum provenance

According to Scope 2, climate change and human health worsen as compared to the concrete option when the aluminum is produced in the USA. When the effects of traffic diversions are added, aluminum remains the best option, regardless of the choice of aluminum supplier.

3.2.5 Comparison with abutment

Another sensitivity analysis was conducted to compare the impact of the abutment and that of the bridge deck. Abutments were modeled as two blocks of 23.25 m^3 of concrete produced in Québec. Materials production, transport, construction and landfilling were considered in the abutments impacts. Figure 13 shows the comparison of LCA results of the bridge deck and abutments.

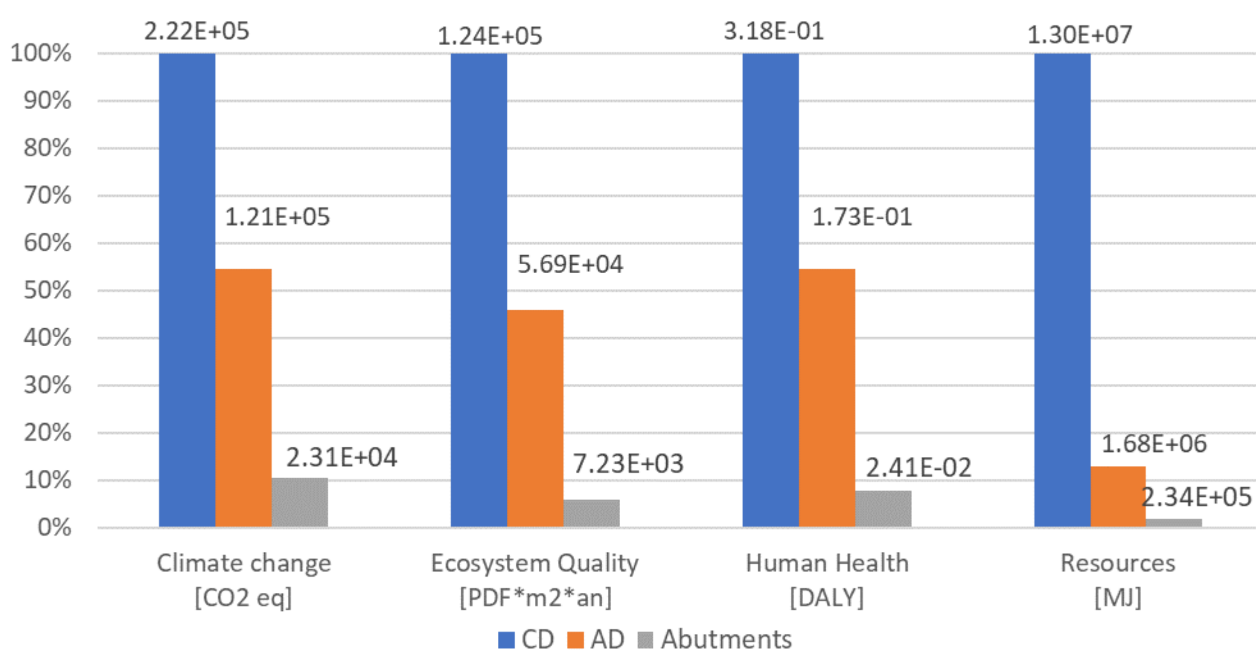


Figure 13: Comparison between abutments and bridge deck (Scope 2)

The impacts of the abutments represent less than 10% of the concrete deck for every indicator. By comparison, abutments are responsible for between 12 and 19% of the total impact for the aluminum deck. This comparison confirms the assumption made early on to exclude the abutment from the scope of the study. A decrease in the environmental impact of the bridge deck decreases the impact of the entire bridge.

3.3 LCA UNCERTAINTY ANALYSIS

The results of the uncertainty analysis obtained from Monte Carlo simulation (1 000 iterations) show no changes to the overall findings of the comparison. Table 5 indicates the difference of impact scores between the concrete and aluminum deck according to Scope 2. Scope 2 excludes major uncertainties related to traffic diversion.

Table 5: Deterministic and probabilistic results of the subtraction of the aluminum deck system from the concrete deck system according to Scope 2. The difference is positive for all indicators, meaning that CD has a greater impact than AD.

	Climate Change [kg CO_2 eq]	Ecosystem Quality [pdf*m2*an]	Human Health [DALY]	Resources [MJ]
Deterministic result	1.01E+05	6.72E+04	1.45E-01	1.13E+07
Median	1.01E+05	6.79E+04	1.45E-01	1.13E+07
5th percentile	9.03E+04	5.94E+04	1.29E-01	1.09E+07
95th e percentile	1.11E+05	8.36E+04	1.61E-01	1.18E+07

Because the values for all indicators are positive, the environmental impacts of the aluminum deck are lower than those of the concrete deck, regardless of all the uncertainties. The difference is only greater when traffic diversion impacts are added.

4 DISCUSSION

4.1 COMPARISON WITH PREVIOUS STUDY

While this is the first LCA and LCC of a short-span aluminium composite bridge deck, it's still possible to compare our results and conclusion to existing literature. The comparisons will be first made on a square meter basis using the climate change indicator. While our analysis have shown a carbon footprint 8 960 kg CO_2 eq /m^2 for CD and 4 870 kg CO_2 eq /m^2 for AD according the scope 2 (complete life cycle without traffic diversion), it is a bit higher than the steel concrete bridge from (Mara et al., 2011) with its 4090 kg CO_2 eq /m^2 and few times higher the concrete slab frame bridges from (Du, Pettersson and Karoumi, 2018) with its 1 370 kg CO_2 eq /m^2. Study from Hammervold et al. (2013) has a ten times lower carbon footprint per m^2 comparison to our study but they considered only routine repair actions and have different bridge design and length.

The contribution analysis can serve as a comparison criterion. In line with our results, (Pang *et al.*, 2015), shows that traffic diversion are up to 75% of the CC results. For the construction stage, as our analysis, the steel and the concrete seem to be the largest contributor (Hammervold, Reenaas and Brattebø, 2013; Du, Pettersson and Karoumi, 2018).

About our LCC results, our scope 2 results, 1114 $ /m^2 for CD and 2734 $ /m^2 for AD, are comparable to (Rantala, 2010) with its 1270 and 1470 Euro /m^2. About our contribution analysis, (Kendall, Keoleian and Helfand, 2008) has shown, like us, that traffic related cost can represented up to 90% of the LCC costs.

A comparison per square meter like we did have some limitation because it assumes that material, maintenance and their associated impact and cost are linearly proportional to the area of the bridge. However, previous comparisons show that our analysis fit in the existing literature on LCA and LCC on bridge deck and that aluminium might lead to some benefits in bridge design.

4.2 ALUMINIUM AS CONSTRUCTION MATERIAL IN BRIDGE

Our analysis has shown that using aluminium in a bridge deck has the possibility to reduce the LCC and the overall environmental impact. However, by looking only at the investment cost, aluminium composite deck is two time more expensive than more common steel-concrete composite deck. The advantages of aluminium are perceived when taking account, the full life cycle including the traffic diversion. A similar trend is observed in the environmental indicators.

While the construction cost and some maintenance cost are insured by the owner of the bridge, generally a government, their evaluation of the best design doesn't not necessarily consider users cost. This dynamic would slow down the adoption of aluminium as a material construction in bridge or any kind of bridge design with higher construction cost but lower life cycle cost. The decision-making process to select the appropriate design for the construction or the rehabilitation of bridges should increase the weight associated with user cost and user environmental impacts in order to have a more holistic approach and a more complete portrait of the situation.

In a broader perspective, the lack of consideration of aluminium in actual construction standards limits innovation in bridge design and force over specifications in design. With the increasing interest of using aluminium in bridge and possible reduction of LCC and LCA impacts, standards should be updated to integrate aluminium as a construction material in bridge.

In the specific context of the province of Quebec, where a significant maintenance deficit in road infrastructure is observed, short-span aluminium composite bridge resulted being a design in line with two first orientations of the latest strategic plan of the ministry: (i) to invest in maintaining the infrastructure of the transport system to ensure a better resilience of the road network and (ii) to ensure an efficient, safe and low carbon transport system to support a strong economy (Ministère des Transports du Québec, 2019). With a local sourcing of aluminium, the maintaining of the road infrastructure could leverage the public founding to not only the construction sector but also the aluminium industry.

4.3 LIMITATIONS

The study involves two key limitations. The first pertains to data availability, particularly the data and parameters that define the maintenance schedules. Although this work is based on the Canadian Highway Bridge Design Code, it relies on important design assumptions, such as structural life (75 years) and the likely oversizing of aluminum extrusion in due to the conservative approach taken by this standard. Scheduled maintenance of the aluminum deck was estimated by MTQ experts and by the researchers who designed the decking. For the concrete option, the maintenance schedule was based on historical data from the MTQ structures division. Owing to the novelty of the aluminum decking, there was no historical data on the long-term behaviours of the structure. Expert assumptions could therefore have a significant impact on the results. The conservative assumptions surrounding the design could have overestimated the cost and impacts of initial construction of the bridge decks. To work around the limitation of a code-based approach, future work should develop a holistic method that includes reliable modeling of structural degradation (Cusson, Lounis and Daigle, 2010)

The second limitation has to do with the long-time horizon of the functional unit. The study covers a 75-year period, which leads to higher uncertainties and a high variability of some parameters. The use of current environmental data to model processes occurring in the future (i.e., maintenance work) introduced some uncertainties into the model.

Road transport electrification could also change the environmental impacts of the bridge detour. Using TIMES-Canada model, Bahn et al. (2013) generated road transport electrification scenarios based on the implementation of different policies. According to their model, in 2050, conventional vehicles will represent 39% of market shares in the baseline scenario and 26% in the energy policy scenario. Knowing that the potential impacts of electric vehicles are 55 to 80% lower than those of conventional vehicles in Québec (CIRAIG, 2016), transport electrification would change the overall results of the study, but not the general conclusions.

The end-of-life treatment of different materials is quite uncertain because waste treatment options are likely to change over the next 75 years. The environmental credits for recycling were based on the assumption of displacing the virgin material production, which is a major contributor to the environment result; the credits were calculated using current data even though the recycling occurs in the future. The aluminum industry may change with breakthrough technologies such as inert anode and wetted drained cathode. These could affect the environmental impacts of aluminum production by removing direct emissions and changing the energy intensity of the smelting process (Obaidat *et al.*, 2018). More broadly, work on the impact of system expansion in LCA to consider the multifunctionality of recycling with a functional unit with a long temporal aspect could be addressed. Environmental credits to the product system are based on today's data, even if the recycling occurs 75 years later and the environmental impacts materials production are likely to change in the next decades.

Another time-related limitation is the methodological difference between LCC and LCA. While LCC applies the discount rate to convert future costs occurring over the entire life cycle to net present value, LCA considers the discount rate differently by separating the short and long terms in the LCI for some elementary flows. The impact assessment method then accounts for this difference by applying different fate factors to short- and long-term emissions. This difference is mainly used for GHG and toxic emissions (Bulle *et al.*, 2019).

4.4 CONCLUSION

This study is the first complete environmental and economic life cycle analysis of an aluminum-steel composite deck. It compares two types of composite short-span bridges—aluminum deck on steel girders and in-situ concrete slab on steel girders—throughout their entire life cycles. Results show that the traffic diversion caused by maintenance activities is the greatest contributor to the cost and environmental impact of both bridges. The higher impact and cost at the construction stage of the aluminum bridge deck vs. concrete slab are offset during the bridge lifetime because a lower maintenance. Aluminum bridge deck should therefore be promoted when the traffic diversion caused by the maintenance works is more than or equal to a flow of 800 vehicles of annual average daily traffic and 5 kilometres of detour (or equivalent).

From the environmental perspective, a bridge with aluminum sourced from Québec is the better option, regardless of the traffic situation. For aluminum sourced from countries with a more carbon intensive electricity mix, the benefits of aluminum decking are less pronounced. Even so, when the indirect impacts of traffic are included, aluminum is still better than the concrete option.

Our analysis demonstrates that a scope limited to the initial construction (i.e., disregarding maintenance and resulting traffic diversion) would generate opposite conclusions. It is therefore critical for bridge designers, decision maker and project leader, to look beyond the purchase and construction costs and consider all life cycle stages to support well-informed decisions for a more sustainable future. In this respect this research work provides a parametrized model to easy the extrapolation of the results of this study in other contexts.

AUTHOR STATEMENTS

ACKNOWLEDGEMENTS

We would like to thank Dominic Fortin, Marie-Hélène Tremblay, Daniel Lavallée and Abdelkader Laoubi from the MTQ for their help in the project. We wish to acknowledge the help provided by Cassandra Bayan. Finally, we also thank Christine Hung for the meticulous proofreading.

This work was supported by Ministry of Transport of Quebec (Project R787.1). A part of the research presented in this paper was financed by the Fonds de Recherche du Québec – Nature et Technologies (FRQNT) (Funder ID: 10.13039/501100003151) by the intermediary of the Aluminium Research Centre – REGAL.

REFERENCE

AAC (2020) *Infrastructure and Bridges*. Available at: https://aluminium.ca/en/aluminium/infrastructure-and-bridges (Accessed: 9 July 2020).

Bahn, O. *et al.* (2013) 'Electrification of the Canadian road transportation sector: A 2050 outlook with TIMES-Canada', *Energy Policy*. Elsevier, 62, pp. 593–606. doi: 10.1016/J.ENPOL.2013.07.023.

Beaulieu, D., Internoscia, J. and Hartileb (2015) *Ponts et passerelles en aluminium - Rapport de visites et de rencontres en Suède, Hollande et aux États-Unis*.

Bulle, C. *et al.* (2019) 'IMPACT World+: a globally regionalized life cycle impact assessment method', *The International Journal of Life Cycle Assessment*. Springer Berlin Heidelberg, pp. 1–22. doi: 10.1007/s11367-019-01583-0.

Burgelin, J.-B. (2017a) *Nouveau concept modulaire de tablier de pont tout aluminium à portée simple et assemblable en chantier*. MSc. Université Laval.

Burgelin, J.-B. (2017b) *Nouveau concept modulaire de tablier de pont tout aluminium à portée simple et assemblable en chantier*. Université Laval.

CIRAIG (2016) *Analyse du cycle de vie comparative des impacts environnementaux potentiel du véhicule électrique et conventionnel dans un contexte d'utilisation québécois*. Available at: www.ciraig.org (Accessed: 7 August 2019).

Cusson, D., Lounis, Z. and Daigle, L. (2010) 'Benefits of internal curing on service life and life-cycle cost of high-performance concrete bridge decks - A case study', *Cement and Concrete Composites*. Elsevier, 32(5), pp. 339–350. doi: 10.1016/j.cemconcomp.2010.02.007.

Daniel, R. A. (2003) 'ENVIRONMENTAL CONSIDERATIONS TO STRUCTURAL MATERIAL SELECTION FOR A BRIDGE', *European Bridge Engineering Conference*. Available at: https://s3.amazonaws.com/academia.edu.documents/35395021/Environmental_Considerations_Rotterdam03.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1525710536&Signature=9TsoVRgRDBZYGed%2FmG998htYnCk%3D&response-content-disposition=inline%3B filename%3DEnv (Accessed: 7 May 2018).

Djedid, A. *et al.* (2019) 'Design and Fabrication of Bridge Decks made from Extruded Aluminium', *Journal of Light Metals Welding*.

Du, G., Pettersson, L. and Karoumi, R. (2018) 'Soil-steel composite bridge: An alternative design solution for short spans considering LCA', *Journal of Cleaner Production*. Elsevier Ltd, 189, pp. 647–661. doi: 10.1016/j.jclepro.2018.04.097.

Eamon, C. D. *et al.* (2012) 'Life-Cycle Cost Analysis of Alternative Reinforcement Materials for Bridge Superstructures Considering Cost and Maintenance Uncertainties', *Journal of Materials in Civil Engineering*, 24(4), pp. 373–380. doi: 10.1061/(ASCE)MT.1943-5533.0000398.

European Aluminium (2019) *Building and construction*. Available at: https://www.european-aluminium.eu/about-aluminium/aluminium-in-use/building-and-construction/ (Accessed: 9 July 2020).

Freeman, C. and Potter, W. (2017) *Aluminium ligthweight orthotropic deck evaluation project*.

Gervásio, H. and da Silva, L. S. (2008) 'Comparative life-cycle analysis of steel-concrete composite bridges', *Structure and Infrastructure Engineering*, 4(4), pp. 251–269. doi: 10.1080/15732470600627325.

Gollier, C. (2013) *Pricing the planet's future : the economics of discounting in an uncertain world*. Princeton University Press.

Government of Canada (2005) *ARCHIVED - Average Exchange Rates for 2003*. Available at: https://www.canada.ca/en/revenue-agency/services/forms-publications/previous-year-forms-publications/archived-rc4152/archived-average-exchange-rates-2003.html (Accessed: 1 August 2019).

Hammervold, J., Reenaas, M. and Brattebø, H. (2013) 'Environmental Life Cycle Assessment of Bridges', *Bridge Engineering*, 18(2), pp. 153–161. doi: 10.1061/(ASCE)BE.1943-5592.0000328.

IAI (2018) *Aluminium in Building – Ballingdon Bridge*. Available at: http://greenbuilding.world-aluminium.org/benefits/light-strong/ballingdon-bridge/ (Accessed: 9 July 2020).

ISO (2006) 'ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework'.

ISO (2017) *ISO 15686-5:2017 - Buildings and constructed assets -- Service life planning -- Part 5: Life-cycle costing*, *Iso*. Available at: https://www.iso.org/standard/61148.html (Accessed: 27 May 2019).

Itoh, Y. and Kitagawa, T. (2003) 'Using CO2emission quantities in bridge lifecycle analysis', *Engineering Structures*, 25(5), pp. 565–577. doi: 10.1016/S0141-0296(02)00167-0.

Jolliet, O. *et al.* (2003) 'IMPACT 2002+: A New Life Cycle Impact Assessment Methodology', *Int J LCA*, 8(6), pp. 324–330.

Kendall, A., Keoleian, G. A. and Helfand, G. E. (2008) 'Integrated Life-Cycle Assessment and Life-Cycle Cost Analysis Model for Concrete Bridge Deck Applications', *Journal of infrastructure systems*. doi: 10.1061/ASCE1076-0342200814:3214.

Kripka, M., Yepes, V. and Milani, C. (2019) 'Selection of Sustainable Short-Span Bridge Design in Brazil', *Sustainability*. MDPI AG, 11(5), p. 1307. doi: 10.3390/su11051307.

Laurent, A., Olsen, S. I. and Hauschild, M. Z. (2012) 'Limitations of Carbon Footprint as Indicator of Environmental Sustainability'. American Chemical Society. doi: 10.1021/ES204163F.

Mader, W. and Pieper, A. (2006) 'Schwansbell bridge celebrating 50th birthday', *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, 16(4), pp. 356–359. doi: 10.2749/101686606778995056.

Mara, V. *et al.* (2011) 'Comparative Study of Different Bridge Concepts Based on Life- Cycle Cost Analyses and Life-Cycle Assessment', pp. 1–6.

Mermer, T. (2012) *Greening the Economy Through Life Cycle Thinking*. Available at: https://www.lifecycleinitiative.org/wp-content/uploads/2013/03/2012_LCI_10_years_28.3.13.pdf (Accessed: 22 July 2019).

Ministère des Transports du Québec (2018) *Rapport annuel de gestion 2017-2018*. Available at: www.transports.gouv.qc.ca (Accessed: 30 July 2019).

Ministère des Transports du Québec (2019) *Plan stratégique 2019-2023*.

Moore, M. A. *et al.* (2004) '"Just give me a number!" Practical values for the social discount rate', *Journal of Policy Analysis and Management*, 23(4), pp. 789–812. doi: 10.1002/pam.20047.

MTMDET (2016) *Guide de l'analyse avantages-coûts des projets publics en transport routier*. Québec, Canada (Ministère des transports, de la Mobilité durable et de l'Électrification des transports).

Obaidat, M. *et al.* (2018) ‘Energy and exergy analyses of different aluminum reduction technologies’, *Sustainability*, 10(4), pp. 1–21. doi: 10.3390/su10041216.

Pang, B. *et al.* (2015) ‘Life cycle environmental impact assessment of a bridge with different strengthening schemes’, *The International Journal of Life Cycle Assessment*. Springer Berlin Heidelberg, 20(9), pp. 1300–1311. doi: 10.1007/s11367-015-0936-1.

Penadés-Plà, V. *et al.* (2020) ‘Environmental and Social Impact Assessment of Optimized Post-Tensioned Concrete Road Bridges’, *Sustainability*. MDPI AG, 12(10), p. 4265. doi: 10.3390/su12104265.

Pizzol, M. *et al.* (2015) ‘Monetary valuation in Life Cycle Assessment: a review’, *Journal of Cleaner Production*. Elsevier, 86, pp. 170–179. doi: 10.1016/J.JCLEPRO.2014.08.007.

Rantala, T. (2010) *Life Cycle Analysis of three Finnish Standard Bridges*.

SCC (2014) ‘CSA S6-14 Canadian Highway Bridge Design Code’.

Siwowski, T. (2006) ‘Aluminium Bridges – Past, Present and Future’, *Structural Engineering International*, 16(4), pp. 286–293. doi: 10.2749/101686606778995137.

St-Gelais, C. (2018) *Comportement strutural d’un platelage en aluminium sur poutre en acier : répartition transversale des charges*. Université Laval.

The Aluminum Association (2020) *Construction and Building*. Available at: https://www.aluminum.org/product-markets/building-construction (Accessed: 9 July 2020).

Vargel, C. (2002) *Corrosion of Aluminium*. Dunod. Paris. Available at: https://books.google.ca/books?id=NAABS5KrVDYC&pg=PA326&dq=corrosion+de+l%27aluminium&hl=en&sa=X&ved=0ahUKEwiC5ffWip7jAhUPZd8KHfNyCyYQ6AEIKjAA#v=onepage&q=corrosion de l’aluminium&f=false (Accessed: 5 July 2019).

Viami International Inc. and The Technology Strategies Group (2013) *Étude de marché sur les possibilités d’utilisation de l’aluminium dans les ponts routiers*. Montréal. Available at: http://docplayer.fr/2250217-Etude-de-marche-sur-les-possibilites-d-utilisation-de-l-aluminium-dans-les-ponts-routiers.html (Accessed: 5 July 2019).

VinMar (2019) *Bimagrip | Bimagrip LS*. Available at: http://www.bimagrip.com/products/bimagrip-ls/ (Accessed: 5 December 2019).

Weidema, B. P. (2009) ‘Using the budget constraint to monetarise impact assessment results’, *Ecological Economics*. Elsevier, 68(6), pp. 1591–1598. doi: 10.1016/J.ECOLECON.2008.01.019.

Weidema, B. P. and Wesnæs, M. S. (1996) ‘Data quality management for life cycle inventories-an example of using data quality indicators’, *Journal of Cleaner Production*. Elsevier, 4(3–4), pp. 167–174. doi: 10.1016/S0959-6526(96)00043-1.

Wernet, G. *et al.* (2016) ‘The ecoinvent database version 3 (part I): overview and methodology’, *The International Journal of Life Cycle Assessment*, 21, pp. 1218–1230. doi: 10.1007/s11367-016-1087-8.