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Life Cycle Cost Assessment of an Existing All-Aluminum Bridge: Comparison of Two Deck Options †

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Abstract: Traditionally, initial material cost has been the governing factor for material selection in structural construction. However, the growing maintenance cost of existing infrastructure has demanded a long-term vision in material selection and in this regard, life cycle cost assessment has been proven to be a better assessment tool than the initial cost of construction. Despite its higher initial cost, aluminum offers many positive attributes, such as a high resistance to weight ratio, good recyclability, and excellent corrosion resistance, which can significantly reduce the life cycle cost of a structure over its entire service life. Yet, the limited use of aluminum in bridge construction and the lack of literature on this matter do not provide comprehensive evidence of its superior performance in the long-term. Based on this premise, this study performs a life cycle cost analysis on the first all-aluminum bridge situated in Arvida, Quebec. The analysis has revealed that most maintenance costs are associated with the rehabilitation of the concrete deck. The frequent concrete deck maintenance dismisses the benefits of the low maintenance aluminum structure. In order to investigate further, an alternative analysis has also been performed on the bridge with a hypothetical aluminum deck that replaces the existing concrete deck. The comparison shows that the aluminum deck reduces the maintenance cost significantly. However, further analysis should be performed with an optimized aluminum deck that can also yield a significantly lower life cycle cost compared to the existing bridge.

Keywords: life cycle cost analysis (LCCA); aluminum bridge; Arvida Bridge; first aluminum bridge

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1. Introduction

Aluminum as a construction material can offer many benefits such as high resistance to weight ratio, excellent corrosion resistance, formability or extrudability, the availability of numerous alloys offering different properties, and better recyclability [1]. Despite these advantages, its application as a primary load-bearing structural member in civil infrastructure is still limited, while it is mostly used in the fabrication of curtain wall or exterior sidings for buildings. In bridge infrastructure, its application is mostly restricted to the decking system or to the construction of pedestrian bridges [2]. One of the primary reasons for aluminum not being the 'material of choice' in bridge infrastructure is its higher initial cost compared to other conventional construction materials such as steel.

Traditionally, the initial cost of the materials is the deciding factor for material selection of structural constructions. With the growing concerns over higher maintenance costs of existing infrastructure, the construction industry is now keen on adopting more holistic approaches, such as the life cycle cost analysis (LCCA) for material selection instead of the initial costs, considering the long-term financial and environmental implications of their projects [3]. Thus, materials such as aluminum with higher initial costs are gaining popularity due to their multitude of positive attributes which can reduce the life cycle cost of structures over their entire service life. However, the current literature is lacking evidence of a comprehensive life cycle cost analysis on an existing aluminum structure. Based on this premise, this study performs a life cycle cost analysis on the first all-aluminum bridge in Arvida, Quebec (represented as 'Arvida Bridge' in the article).

2. Description of the Arvida Bridge

The Arvida Bridge is the longest aluminum bridge in the world, constructed with the Alcan 26S-T (equivalent to the 2014-T6) alloy due to its high mechanical properties, with a yield strength (Fy) of 395 MPa and an ultimate strength (Fu) of 440 MPa [4]. The bridge is designed as an arch-deck type bridge with a total span of 153 m, where the main span of 90 m crossing the Saguenay River is constructed with two parabolic arches as shown in Figure 1. The ribs of the arch are built with box girder sections that are fabricated from aluminum plates connected with rivets and braced by a K-system of lattice girders. The deck is built with a 200 mm reinforced concrete slab, which is supported by 779 mm deep built-up I-shaped floor beams resting on posts assigned every 6 m. The deck is elevated at a height of 33 m above the river. A rigid frame fabricated from an aluminum plate assembly is also provided to support the deck on each side of the main span in order to sustain lateral wind loads. A bracket system with 1200 mm long cantilever floor beam is also provided to support the walkway on each side of the bridge. All the roadway loads are being carried by the two main longitudinal girders or stringers which are shaped exactly like the floor beams.

Figure 1. Arvida Bridge, Québec, Canada (picture taken by Thomas Fortin).

3. Life Cycle Cost Analysis (LCCA) of the Arvida Bridge

3.1. Scope

LCCA is a tool to determine the total cost of a structure including all the past and future costs associated with the structure during all phases of its design life. This method is standardized by the International Organisation for Standardization through its code ISO 15686-5 (Buildings and constructed assets—Service life planning—Part 5: Life cycle costing) [5]. The first step of a LCCA is to determine the scopes and objectives of the analysis, based on which different options can be considered. In the case of the Arvida Bridge, the goal is to assess its long-term economic performance over its service life, which has been chosen as 100 years. The life cycle costs include both past and future costs. Past costs include the construction cost and all the maintenance-related costs carried out on the bridge as reported by the Ministère des Transports (MTQ). The future costs include all costs related to the future maintenance and the demolition of the bridge. Moreover, indirect costs such as the cost of traffic disturbances impacting the users of the bridge have been included in the analysis. Due to the lack of data, the costs of inspections and minor maintenance are not considered in this analysis, which is believed to have less influence on the final observations of this study. Another important aspect of the LCCA is to harmonize the time difference in the occurrence of all different types of costs throughout the entire life span of the bridge. To do so, every cost has been converted to July 2022 (the beginning of the analysis) in Canadian Dollars, considering a discount rate of 2.37% as recommended by the MTQ [6]. The inflation of the past costs is taken from the Bank of Canada's historic economic data [7].

3.2. Methodology

Based on the scope of this study and the ISO 15686-5 standard criteria [5], all direct and indirect costs as mentioned earlier are estimated. The past maintenance costs from 1950 to 2022 have been calculated based on the report provided by the MTQ, while the projected maintenance and demolition costs are estimated until its end of life which is 2050. Finally, the key indirect costs, specifically the traffic disturbance costs associated with the maintenance, have been calculated. The following sections describe the detailed procedure used to estimate these above-mentioned costs and perform the life cycle cost analysis.

3.2.1. Construction and Past Maintenance Costs

The construction and past maintenance costs extracted from the database of MTQ can be considered as real costs, with the amounts of a currency having a value for a specific time. However, with inflation over time, this value fluctuates. Hence, to perform the LCCA, every cost should be converted to the same current value corresponding to a base date, known as the nominal cost. In this study, the base date is July 2022. Hence, all the construction and past maintenance costs are converted to the nominal cost based on the base date of July 2022. To do so, the following formula is employed:

$$q_i = (1 + d)^n \tag{1}$$

where, q_i is multiplied with the past costs to convert them to the base date value, d is the percentage increase in prices per annum, and n is the number of years between the base date and the occurrence of the cost. In this study, d has been determined as 2.37% as per the Guide de l'analyse avantages-coûts des projets publics en transport routier [6].

3.2.2. Future Maintenance and Demolition Work

With respect to the base date of 2022, the remaining useful life of the bridge is 28 years. Hence, the future maintenance costs for the 28 years and the demolition costs at the end of its useful life need to be estimated. The future maintenance works have been projected following two guidelines. Firstly, the current state of the deterioration of the bridge is assessed by reviewing the inspection report from the MTQ [8]. The report provides the details of the deterioration level of every component of the bridge. It also recommends which elements need to be replaced or to be closely monitored in the future. Secondly, the actual past maintenance record of the bridge is also helpful to project the future maintenance works that are necessary on the bridge. Finally, the costs of different construction activities concerning MTQ's infrastructure between 2018 and 2020 that are listed in the Liste et prix des ouvrages d'infrastructures de transport [9] have been useful in projecting these future costs. Similar to the past costs, the future costs need to be projected to the base date using the following multiplication factor:

$$q_d = \frac{1}{(1 + d)^n} \tag{2}$$

where, d is the discount rate per annum assumed as 2.37% as recommended by the MTQ and n is the number of years between the base date and the occurrence of the cost.

3.2.3. Traffic Disturbance Costs

The previously mentioned costs are direct costs. However, for an accurate LCCA of a structure, it is necessary to include all the major indirect costs in the analysis, such as traffic disturbance costs, which play a crucial role in the cost distribution. The user cost includes time lost costs, fuel costs, and vehicle maintenance and depreciation costs. Multiple factors are taken into account in the calculations of those costs such as:

- The duration of the road closure during maintenance works;
- The average annual daily traffic (*AADT*);
- The percentage of the *AADT* that are trucks;
- The parameters of the traffic detour (length and speed);
- The cost of vehicles lost time;
- The fuel, maintenance, and depreciation costs of vehicles.

The duration of the closure of the bridge during maintenance is the main factor impacting the traffic disturbance costs. The information on the work schedule of the past maintenance works is partially available. Also, some of the repair work did not necessitate closing the roadway of the bridge. Unspecified past and future maintenance work has been estimated on the basis of the importance of the work.

Average annual daily traffic (*AADT*) is the number of vehicles that cross the bridge daily. Primarily, AADT is determined by monitoring the passages on multiple days throughout the year and calculating the daily mean for a more representative value. The municipality of Jonquière, who is responsible for the roads on each shore of the bridge, has provided the number of passages on the bridge in 2013, with the total number of crossings of vehicles being 1010. To consider the yearly increase in *AADT* and to estimate the past number of vehicles crossing the bridge, a percentage of annual variation in the *AADT* is used. For rural roads, a yearly increase of 1% is recommended. In addition to the *AADT*, it is also important to know the type of vehicles that are frequent on the structure. Indeed, the operation cost of a truck is greater than a light car. Accordingly, it is assumed that 2.0% of the AADT are trucks, which has been specified by the MTQ.

The location of the work closure also affects the indirect cost of maintenance. Depending on the geographical situation of the bridge, the length, and the speed limit of the detour by the vehicles compared to their regular itinerary is a relevant factor in deciding the indirect costs. The detour also has a direct impact on users' daily activities. It not only increases their commute time but also can create delivery delays for companies. The surrounding community is also affected by the road closure creating potential productivity loss. In the current study, an 8 km detour length was utilized based on the surrounding road network. To account for such time losses due to the detour of a route, an hourly price has been determined by the MTQ depending on the types of vehicles and the objectives of the transportation. The following equation allows to quantify the cost of lost time due to road closure [6]:

$$Cost_{time} = \left(\frac{L_{Detour}}{S_{Detour}} - \frac{L_{Bridge}}{S_{Bridge}}\right) \times AADT \times N_{closure} \times n_{occupancy} \times \alpha \tag{3}$$

where, L_{Detour} is the length of the detour, L_{Bridge} is the length of the bridge, S_{Detour} is the speed limit taking the detour, S_{Bridge} is the speed limit on the bridge, $AADT$ is the average annual daily traffic, $N_{closure}$ is the number of days of closure of the bridge during maintenance operations, $n_{occupancy}$ is the number of passengers in each vehicle, and α is the hourly cost of the displacement depending on the type of vehicle and the commute reasons [6].

Finally, the calculation of user delay cost depends on the detour parameters, *AADT*, vehicle types, and the length of the closure. The Equations (4) and (5) respectively quantify the fuel costs and maintenance and depreciation costs.

$$Cost_{price} = (L_{detour} \times \beta_{S.detour}) - \left(L_{bridge} \times \beta_{S.bridge}\right) * AADT \times N_{closure} \tag{4}$$

$$Cost_{depreciation} = \left(L_{detour} - L_{bridge}\right) \times AADT \times N_{closure} \times \gamma \tag{5}$$

where, $\beta_{S.detour}$ is the fuel consumption cost for the speed limit of the detour, $\beta_{S.bridge}$ is the fuel consumption cost for the speed limit on the bridge, and γ is the depreciation and maintenance cost depending on the type of vehicle.

3.3. Results and Discussions

Figure 2 shows the distribution of the different costs through the life span of the bridge, i.e., from 1950 to 2050. The primary data extracted from the analysis are the total cost of acquisition (also known as total life cycle cost) of the bridge which is CAD 11,918,161.64 as of July 2022. Figure 2 also highlights the significant cost associated with maintenance works, more specifically the deck rehabilitation in 2013 which accounts for 36% of the total cost. The higher cost of this rehabilitation along with the associated long closure period of the bridge adds up to an important portion of the total cost.

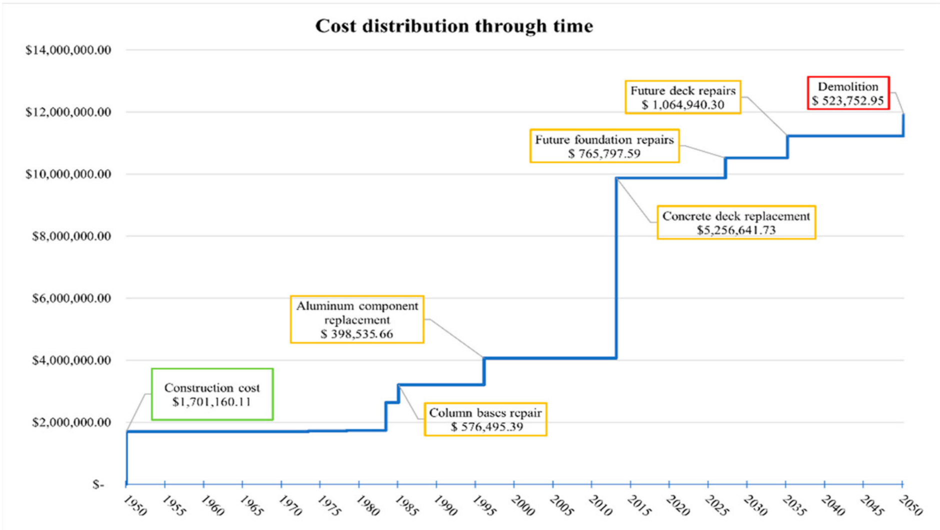

Figure 2. Life cycle cost distribution of the Arvida bridge over time.

To more efficiently represent the participation of the different categories of cost in the total cost of acquisition, Figure 3 has been generated. It can be seen that maintenance work contributes the most to the total cost, which is approximately half of the total cost of acquisition. With 31.3% of the total cost, the traffic disturbance costs also play a crucial role. Moreover, the detour caused by the deck reconstruction in 2013 contributes around 12% to the total cost of the bridge. The construction and demolition of the bridge account for approximately 20% of the total cost. Evidently, the maintenance and traffic disturbance costs are the major contributors, which are higher than the initial costs of construction. This highlights the importance of LCCA as the potential decision-making tool for a construction project rather than the initial construction cost.

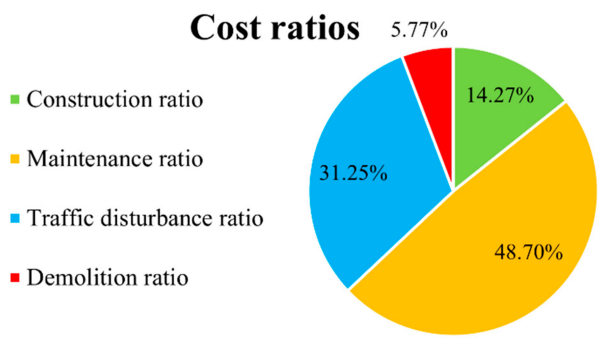

Figure 3. Proportions of each cost in the total life cycle cost of the Arvida Bridge.

3.4. Alternative Analysis with Aluminum Deck

As it is evident from the LCCA that the rehabilitation of the concrete deck contributed maximum to the total cost of acquisition, an alternative analysis was performed with a hypothetical aluminum deck on the existing Arvida bridge structure. This analysis was primarily conducted to better understand the long-term economic performance of aluminum as a bridge construction material in lowering the maintenance cost of the Arvida Bridge. The aluminum deck used for this analysis was designed in the research project R786.1 in partnership with Université Laval and the MTQ [10]. This 6061-T6 alloy extrusion, as shown in Figure 4, is structurally adequate for the current girder configuration of the Arvida Bridge, which was confirmed through performing a structural analysis of the bridge with the aluminum deck. It should be noted that no in-depth analysis or design has been undertaken to optimize the overall bridge structure with the new deck. The lightweight characteristic of the aluminum deck along with the wearing surface with Bimagrip coating has reduced the dead weight of the structure significantly.

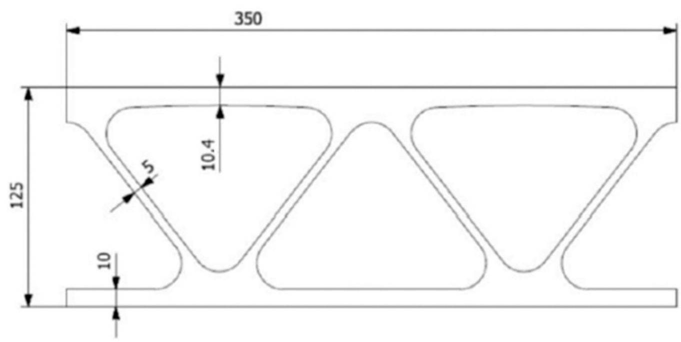

Figure 4. Extruded aluminum deck as developed in the research project R786.1 (Figure courtesy of Amar Djedid) [10].

The life cycle cost analysis of this alternative bridge configuration has been performed following the same methodology and parameters as the original analysis. The construction cost of the bridge with the aluminum deck has been estimated along with the maintenance costs associated with the aluminum deck as described below [11]:

- Bimagrip coating replacement every 25 years;
- Inferior deck bolts replacement every 25 years;
- Superior deck bolts replacement every 50 years.

The graph shown in Figure 5 compares the cost distributions over the life span of the original (concrete deck) and alternative (aluminum deck) bridge structures. The total cost of acquisition of the alternative analysis amounts to CAD 12,408,407.03 which is 4.1% (CAD 490,245.40) higher than the cost of the original bridge. This higher value is mainly contributed to by the higher construction cost of the bridge with the aluminum deck, which is nearly three times the construction cost of the original bridge. However, the low maintenance costs of the alternative bridge over its 100 years of life span have nearly compensated for the higher initial cost. It should be noted that this higher value of the total cost can be easily compensated if the aluminum deck is optimized based on the current configuration of the bridge, which is out of the scope of this study.

To further analyze the costs, Figure 6 compares the costs by category of these two options. There are significant differences in the distribution of the cost, for example, in terms of the construction and maintenance costs as discussed earlier. In addition, there is a 20% reduction in traffic disturbance costs associated with the alternative deck solution. In terms of lump sum amounts, the reductions in the maintenance and traffic disturbance costs represent approximately 1.9 and 2.3 million dollars, respectively. In this context, it should be noted the direct maintenance costs of the concrete deck and its wearing surface is 2.8 million dollars, whereas it is 0.9 million dollars for the aluminum deck. Despite the slightly higher acquisition cost of the alternative bridge configuration, it is believed that the advantage of an aluminum deck will be prominent in terms of maintenance costs, while the higher initial cost of the deck can be reduced significantly if the deck is designed optimally for the Arvida bridge structure. It is certain from the LCCA analysis that the low-maintenance aluminum is a durable solution for bridges under cold and corroding environments like in Canada.

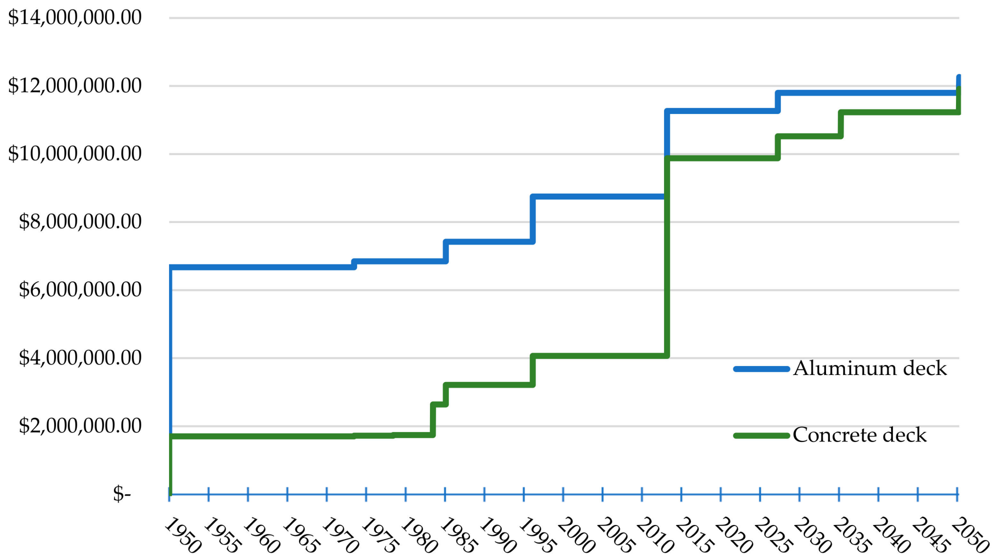

Figure 5. Comparisons of LCCA cost distributions over time in the case of the concrete and aluminum decking options.

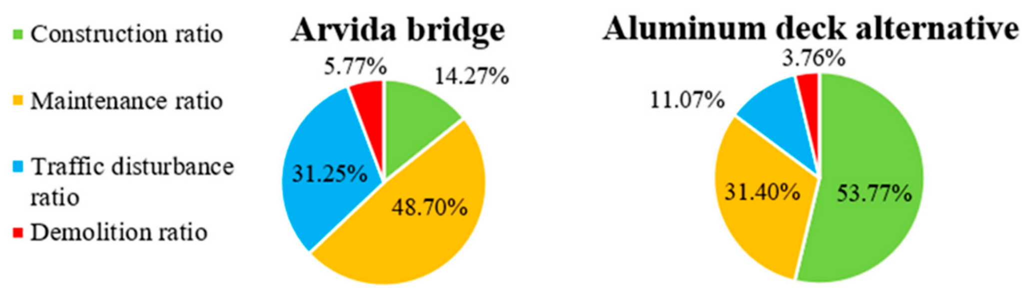

Figure 6. Comparison of LCCA cost proportions by categories in the case of the concrete and aluminum decking options.

4. Conclusions

The life cycle cost analysis performed in this study has allowed to determine all the relevant costs associated with the Arvida bridge in its lifetime. The outcomes from this study have revealed that maintenance of the existing bridge accounts for nearly 50% of the total cost, with the majority of the maintenance costs associated with concrete rehabilitation. The frequent concrete repairs combined with the long curing period of the current deck dismiss all the advantages of the low-maintenance aluminum structure. A comparison of these LCCA results with the alternative LCCA performed on the bridge with an alternative aluminum deck has shown that an aluminum deck can significantly reduce the costs associated with the maintenance and traffic disturbance costs, while the higher initial costs concerning the aluminum deck can be reduced through optimally designing the deck to be suitable for the current bridge configuration. Overall, aluminum is a sustainable solution for bridge infrastructure, especially for those located in cold and corroding environments and needing frequent maintenance. Nevertheless, further analysis with an optimized aluminum deck should be performed on this bridge for a better understanding of the benefit of a 100% aluminum bridge structure including the deck.

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