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Comparison between major repair and replacement options for a bridge deck life cycle assessment: A case study

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Abstract. Material production, manufacturing, transportation, usage, and end of lifeprocessing are usually the main contributors defining the life cycle assessment (LCA). Bridge infrastructure is important to the economy and the society. Over their life cycle, highway bridges experience several stressors that can significantly affect their structural performance and therefore require rehabilitation. This paper discusses the life cycle analysis of bridge rehabilitation decisions and demonstrates the analysis with a case study of a bridge located in Ontario, Canada. The LCA of the bridge deck is analyzed for two rehabilitation strategies: major repair and replacement. The study focuses on evaluating the different life cycle phases of the bridge deck by assessing their carbon dioxide emission, energy consumption and cost. Also, the paper presents the impact of the different elements within each phase to identify the most contributing elements. The LCA of the bridge deck is analyzed and estimated with the aid of CES EduPack 2016 software that includes a database of more than 4000 different materials and more than 200 manufacturing processes. Analysis of the case study shows that material phase causes significant life cycle impact. The study concluded that the deck replacement yields higher environmental impact and life cycle cost compared to repairing and strengthening the deck.

1 Introduction

Life cycle assessment (LCA) is a comprehensive, standardized, and internationally recognized approach used to quantify the environmental impacts in terms of resources consumption, waste production and gas emission, and any other related environmental impacts attributable to a service, asset, or a product [1, 2]. Sustainability requirements covering impacts on the environment, economy, and society can be evaluated for a certain project or product through studying its life cycle impact. Bridge management decisions, including maintenance, repair and replacement (MR&R) have direct implications on the environment, the society and the economy. Material production, transportation,

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construction operations, maintenance and repair, and end of life phases are usually considered and assessed in bridge life cycle analysis. All the life cycle phases associated with the bridge should be identified and assessed starting from the material production phase and ending with end of life phase. The material production is generally causing the most impacts, and maintenance and repair phase of the asset comes in the second level [3]. The production of cement and the sourcing of aggregates, as the main constituent martials of concrete, have significant impact on the environment mainly in terms of the non-renewable natural resources, energy consumption and carbon dioxide emissions [4]. Every tonne of cement production releases 1.0 – 1.2 tonne of CO_2 into the environment by the time the material is put in place [5].

This research attempts to perform life cycle assessment of a bridge deck in terms of environmental impacts and cost while considering all the different phases of the deck life cycle. The LCA will be performed for bridge major repair and replacement rehabilitation options. The study aims to demonstrate the environmental impacts and cost of the different phases and attempts to address the following questions: 1) identifying the occurrence of these environmental impacts within the bridge life cycle, 2) what are the most dominant phases in terms of environmental impacts and cost throughout the bridge life cycle, and 3) what are the effects of alternative recycling options on environmental impacts. The LCA of the bridge will be demonstrated through CES EduPack 2016 software with databases that include more than 4000 different materials and more than 200 manufacturing processes. The software can analyze the LCA of a bridge deck including both cost and environmental impacts during material, manufacture, transport, use, and end of life phases.

2 Proposed assessment framework of bridge deck

The bridge life cycle starts with material production and ends with the bridge demolition. Over the bridge life cycle, MR&R decisions contribute significantly to the total impact on the environment, the society and the economy. Steele et al. (2003) reported that construction material of a bridge has significant impact on the LCA and reducing the amount of material used can significantly reduce the impact on the environment, but this target should not compromise the durability and longevity of the structure. In addition, sufficient maintenance strategies could prevent deterioration and extend the structural life. Most of studies show that bridge replacement represents higher environmental impacts than refurbishment and strengthening of the bridge [6]. The proposed framework in this paper focuses on the impact assessment of major repair and replacement decisions. Figure 1 below shows a flowchart for the rehabilitation strategies and their potential impacts to be considered in this research.

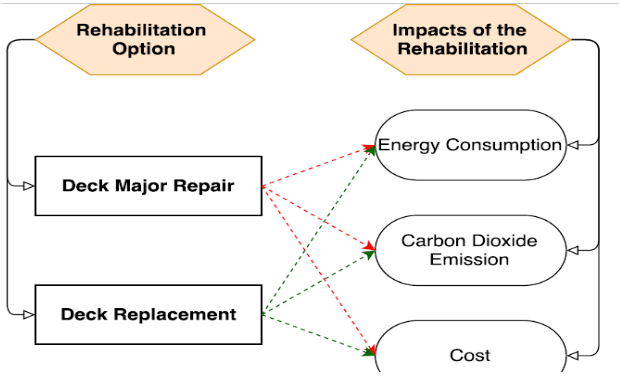

Fig. 1. Flow chart for the rehabilitation options and impacts of each.

Manufacturing of steel and concrete, which are the predominant materials for bridges construction, contribute the most to environmental impacts over the structure life cycle [6]. The bridge superstructure components include the bridge deck and its overlay and accessories, the girders, and the expansion joints. These elements require large amount of raw materials and contribute most to the environmental impacts during the material production phase. In addition, construction equipment and machineries such as earthwork excavators, compactors, cranes and many others used during construction phase contribute to the environmental impacts through energy consumption and emissions [1], [2]. The bridge construction phase accounts relatively for lower environmental impacts compared to the material production phase. It should be noted that the operation phase contributes significantly to the impacts on the environment. On the other hand, usually the transportation of construction material and equipment during the bridge different life cycle phases are of minor importance and of limited impacts on the environment [7]. The assessment of the end of life phase is associated uncertainties due to the dependency on future technologies that could take place after 50 to 100 years of a bridge service life. The environmental impacts of this stage involve the energy consumption through several activities which are mainly the demolition of the structure, sorting, transportation, and a final treatment of the generated wastes that may include reusing, recycling, or placing in landfills [1, 2]. Within the framework of the proposed analysis in this paper, the different life phases of the bridge deck and their impacts are assessed with respect to energy consumption, CO2 emission and direct cost as displayed in Figure 2. The definitions of the different phases are provided in the following sections.

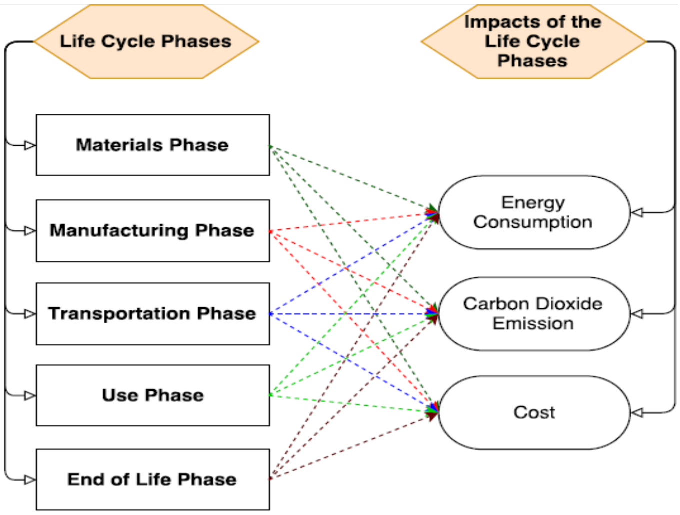

Fig. 2. Flowchart of the dzifferent life cycle phases and their impacts.

2.1 Materials phase

The material phase is considered as the most contributing phase in terms of impact on the environment. The selection of the material type has significant impact on the processes, including the consumption quantity, maintenance activities, and end of life consequences [8]. This phase captures the extraction and production of the raw materials from their original shape and source to be ready for the next phase which is the manufacturing process. Usually material production phase counts for the highest impacts on the environment [3, 7, 8].

2.2 Manufacturing and transportation phases

The manufacturing phase accounts for the different material manufacture processes. This phase starts with extracting the raw material and ends with transporting the ready products to the construction site. Transportation is the third phase in bridge life cycle assessment. This phase includes the energy consumed, carbon dioxide emitted and cost utilized during the transportation of the final products from the manufacturing plant to the construction site.

2.3 Use phase

The use phase is considered as the longest phase in bridge's life cycle and typically contains operation, repair, and routine maintenance activities [7, 8]. Different contributors are impacting the bridge structure during the use phase. Among these, traffic is the main contributor to the environmental impact. The impacts from the traffic are not included in the analysis herein due to two main reasons. First, the CO_2 emissions and the energy consumption due to the traffic will be extremely high compared to the impacts of the other phases during the expected life period of the bridge deck (25 years). However, this impact is equivalent for all of the considered rehabilitation strategies, given that the bridge serves the same number of vehicles during this phase. As a result, including the traffic impact from all the alternatives or excluding it will not affect the final results obtained from the assessment. The second reason is that the traffic is not an element of the bridge structure and therefore quantifying its environmental impacts needs to be separated from the maintenance management decision making. The analysis excludes the impact from traffic so its significant impact does not undermine the importance of the impact attained from the main elements of the bridge structure.

2.4 End of life phase

The end of life phase includes several events starting with bridge demolition, waste sorting, material recycling, and ending up with final landfill. Usually the EOL phase generate treated and recycled materials that result in benefiting the environment. To quantify the benefits out of the EOL phase for a certain project, they should be measured from the next project where the recycled material is used[8].

A detailed representation of the environmental impacts due to the deck major repair through the different life phases is shown in Figure 3 and Table 3 below. In addition, Table 4 shows the components that most contribute to the energy consumption, CO_2, and cost in the different life phases of the bridge deck major repair.

3 Bridge deck LCA: a case study

The bridge considered for this study is located in Ontario, Canada and was constructed in 1965. The deck is a three-span solid post tensioned concrete slab with a thickness of 381 mm. The five different phases considered in this study for the bridge deck life cycle assessment are: the materials phase, the manufacturing phase, the transportation phase, the use phase, and end of life phase are. The materials and their respective quantities included in this study were taken from a bill of quantity provided by Ontario department of transportation for the mentioned bridge above. The different material types were selected using the material database within the CES EduPack software. The thickness of the different materials was reasonably assumed and then the masses were calculated accordingly. The analysis was performed per unit area of the bridge deck.

To analyze the environmental impacts due to bridge's deck major repair and replacement events through CES EduPack software, three main entities need to be specified. First entity is the material,manufacture, and end of life phases. The bill of quantity of the material is an input to the software with each line representing an individual component. Quantity, component name, material, recycled content, mass, primary and secondary processes, percentage removed, and end of life are the main entry fields for the material, manufacture, and end of life phases. Second is the transport filed which accounts for the transportation of the finished products from the place of manufacturing to the construction site. The third and last entity for the analysis of the environmental impacts of the bridge deck rehabilitation event is the use filed. This field includes the product life, country electricity mix, and modes of use (static and/or mobile modes).

Once the needed information are entered into the software, the relative contributions of the different phases on the environment in terms of the energy consumption, carbon dioxide emission, and cost can be assessed. Also, the contribution of the diffident elements within each phase are compared to identify the elements with the highest impacts on the environment. The final results are demonstrated with figures and bar charts for both rehabilitation options: the major repair and the replacement of the deck. Table 1 and 2 below show the deck components, masses, primary processes, secondary processes, EOL scenarios and percentages recovered for deck major repair and replacement options respectively.

Table 1. Related information for the bridge deck major repair.

Item #	Item Description	Mass (Kg)	Primary Process	Secondary Process	EOL	% Recovered
1	Removal of asphalt wearing surface	250.0	Incl. in material value	Cutting and trimming	Landfill	0.0
2	Removal railing	2859.6	Forging		Recycle	25.0
3	Removal of concrete curbs	914.4	Incl. in material value		Landfill	0.0
4	Type A removals from top of deck (determinations only)	360.0	Incl. in material value		Landfill	0.0
5	Type B removal from deck soffit	240.0	Incl. in material value		Landfill	0.0
6	Type C removals from fascia	240.0	Incl. in material value		Landfill	0.0
7	Type C removal from deck ends (tendon anchors)	74.4	Incl. in material value		Landfill	0.0
8	Removal of existing approach slab	540.0	Incl. in material value		Recycle	5.0
9	Granular backfill	2015.0	Incl. in material value		Landfill	0.0
10	Scarify deck surface	19.2	Incl. in material value		Landfill	0.0
11	Cathodic protection	14.4	Incl. in material value		Landfill	0.0
12	Abrasive blast cleaning of rebar	1.9	Forging		Landfill	0.0
13	Abrasive blast cleaning for overlays	0.7	Incl. in material value		Landfill	0.0
14	Concrete overlay (includes padding for new crowns)	600.0	Incl. in material value		Landfill	0.0
15	Finish and cure overlay	144.0	Incl. in material value		Landfill	0.0

16	Concrete barrier wall	960.0	Incl. in material value		Landfill	0.0
17	Concrete in new deck extensions	914.4	Incl. in material value		Recycle	5.0
18	Concrete in approach slabs	540.0	Incl. in material value		Landfill	0.0
19	Stainless steel rebar (barrier wall & deck extensions)	95.6	Forging		Recycle	20.0
20	Coated rebar for overlay padding area	141.3	Forging		Recycle	15.0
21	Rebars in deck extensions	143.5	Forging		Recycle	15.0
22	Rebars in approach slabs	143.5	Forging		Recycle	15.0
23	Abutment repairs	1464.0	Incl. in material value		Recycle	5.0
24	Deck soffit repairs	360.0	Incl. in material value		Landfill	0.0
25	Bridge deck waterproofing	6.0	Polymer molding		Landfill	0.0
26	Asphalt	232.5	Incl. in material value		Recycle	15.0

Table 2. Related information for the bridge deck replacement.

Item #	Item Description	Mass (Kg)	Primary Process	Secondary Process	EOL	% Recovered
1	Removal of asphalt wearing surface	250.0	Incl. in material value	Cutting and trimming	Landfill	0.0
2	Removal railing	2859.6	Forging	Cutting and trimming	Recycle	25.0
3	Removal of existing decks including curbs	914.4	Incl. in material value	Cutting and trimming	Landfill	0.0
4	Removal of top of pier	600.0	Incl. in material value	Cutting and trimming	Recycle	10.0
5	Removal of existing approach slab	540.0	Incl. in material value	Cutting and trimming	Landfill	0.0
6	Granular backfill	2015.0	Incl. in material value	Grinding	Landfill	0.0
7	Concrete in new top of existing piers	1096.8	Incl. in material value	Cutting and trimming	Landfill	0.0
8	Prestressed members (fabrication and erection)	600.0	Incl. in material value	Cutting and trimming	Landfill	0.0
9	Concrete in barrier wall	960.0	Incl. in material value	Cutting and trimming	Landfill	0.0
10	Concrete in deck (150 mm topping)	360.0	Incl. in material value	Cutting and trimming	Recycle	5.0
11	Concrete in new deck extensions	914.4	Incl. in material value	Cutting and trimming	Recycle	5.0
12	Concrete in approach slabs	540.0	Incl. in material value	Cutting and trimming	Recycle	5.0
13	Stainless steel rebar in barrier wall	95.6	Forging	Cutting and trimming	Recycle	20.0
14	Coated rebars in deck topping	141.3	Forging	Cutting and trimming	Recycle	15.0
15	Rebars in deck extensions	143.5	Forging	Cutting and trimming	Recycle	15.0
16	Rebars in approach slabs	143.5	Forging	Cutting and trimming	Recycle	15.0
17	Bearings	425.5	Forging	Cutting and trimming	Recycle	20.0
18	Abutment repairs	1464.0	Incl. in material value	Cutting and trimming	Recycle	5.0

19	Bridge deck waterproofing	6.0	Polymer molding	Cutting and trimming	Landfill	0.0
20	Asphalt	232.5	Incl. in material value	Cutting and trimming	Recycle	15.0

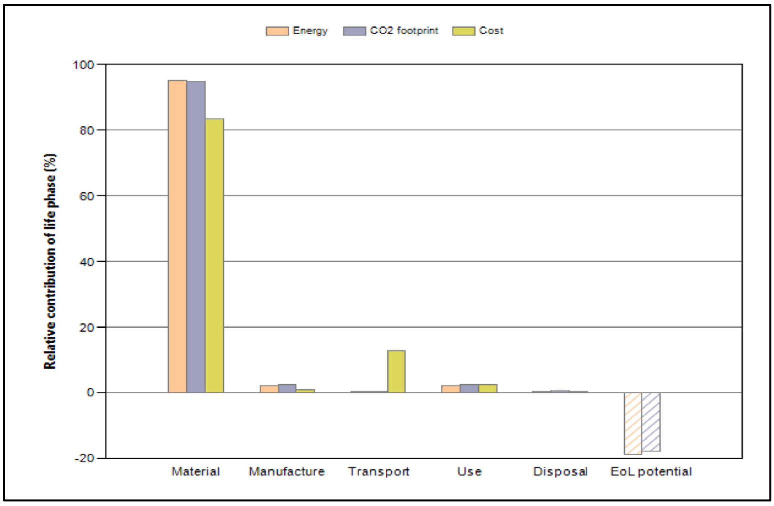

Fig. 3. Relative contribution of the different phases in terms of energy, CO2, and cost for deck major repair.

Table 3. Energy consumption, CO2 emission, and cost of the different phases for bridge deck major repair.

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	6.2x10^{11}	95.1	41826.5	94.7	15823.1	83.4
Manufacture	1.4x10^{10}	2.2	1056.0	2.4	165.1	0.9
Transport	1.8x10^{8}	0.0	13.0	0.0	2415.7	12.7
Use	1.5x10^{10}	2.3	1060.3	2.4	483.4	2.5
Disposal	3.1x10^{9}	0.5	220.1	0.5	85.2	0.4
Total (for first life)	6.5x10^{11}	100	44175.9	100	18972.4	100
End of life potential	-1.2x10^{11}		-7866.6			

Table 4. Deck components with maximum contribution in the different life phases for deck major repair.

Phase	Deck component with max. contribution	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	Removal of railing	5.7x10^{11}	91.6	3.8x10^{4}	89.8	1.2x10^{4}	73.2
Manufacture	Removal of railing	1.3x10^{10}	88.9	939.2	88.9	74.4	45.1
Transport	Granular backfill	2.8x10^{7}	15.2	2.0	15.2	366.7	15.2
Use (mobile mode)	Abutment repairs	1.7x10^{9}	11.0	116.9	11.0	53.3	11.0
Disposal	Removal of railing	9.3x10^{8}	29.6	65.1	29.6	18.4	21.5
End of life potential	Removal of railing	-1.2x10^{11}	95.6	-7.5x10^{3}	95.1	-	-

Figure 4 and Table 5 below present the environmental impacts due to the deck replacement through the different life phases Also, Table 6 shows the components that most contribute to the energy consumption, the CO_2 emission and cost in the different life phases of the bridge deck replacement.

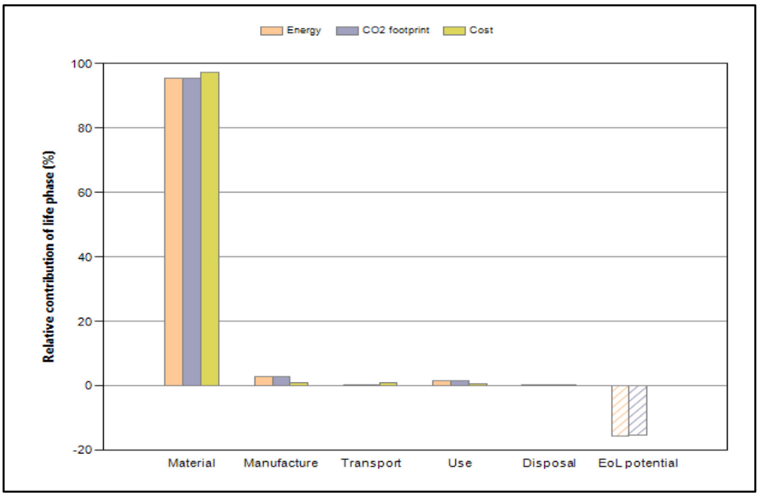

Fig. 4. Relative contribution of the different phases in terms of energy, CO2, and cost for deck replacement.

Table 5. Energy consumption, CO2 emission, and cost of the different phases for bridge deck replacement.

Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	3.6x10^{12}	95.4	254659.5	95.3	286753.9	97.5
Manufacture	1.0x10^{11}	2.7	7595.2	2.8	2962.3	1.0
Transport	6.8x10^{8}	0.0	48.6	0.0	2415.7	0.8
Use	5.6x10^{10}	1.5	3963.3	1.5	1806.9	0.6
Disposal	1.4x10^{10}	0.4	981.9	0.4	318.6	0.1
Total (for first life)	3.8x10^{12}	100	267248.4	100	294257.4	100
End of life potential	-5.9x10^{11}		-40644.5			

Table 6. Deck components with maximum contribution in the different life phases for deck replacement.

Phase	Deck component with max. contribution	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	Bearings	3.0x10^{12}	82.7	3.8x10^{4}	89.8	2.7x10^{5}	94.5
Manufacture	Bearings	8.7x10^{10}	86.1	6.5x10^{3}	86.1	2.8x10^{3}	94.6
Transport	Bearings	4.9x10^{8}	72.0	35.0	72.0	1.7x10^{3}	72.0
Use (mobile mode)	Bearings	4.0x10^{10}	72.0	2.9x10^{3}	72.0	1.3x10^{3}	72.0
Disposal	Bearings	1.1x10^{10}	76.4	750.0	76.4	230.0	72.0
End of life potential	Bearings	-4.7x10^{11}	79.1	-3.3x10^{4}	80.6	-	-

Table 7 shows the total energy consumption, total carbon dioxide emission, and total cost for deck major repair and replacement options. Also, Figures 5 – 7 show a graphical comparison for the environmental impacts caused by both rehabilitation options in the different life phases.

Table 7. Energy consumption, carbon dioxide emission, and cost per unit area per year for both rehabilitation options.

Rehabilitation option	Energy consumption (J/year)	CO_2 emission (Kg/year)	Cost (USD/year)
Deck major repair	2.6×10^{10}	1767.0	758.9
Deck replacement	1.5×10^{11}	10689.9	11770.3

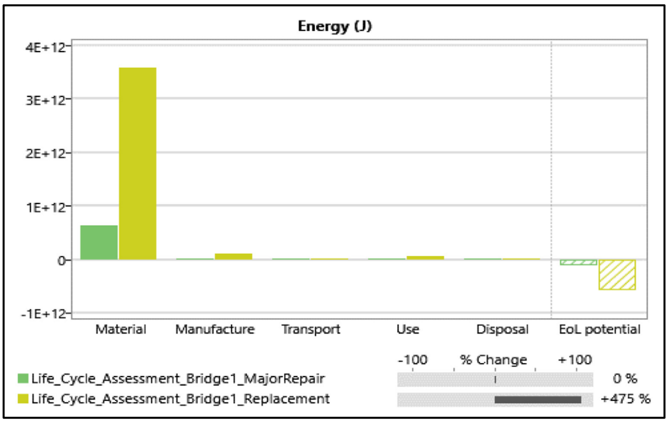

Fig. 5. Comparison of energy consumption for major repair and replacement options.

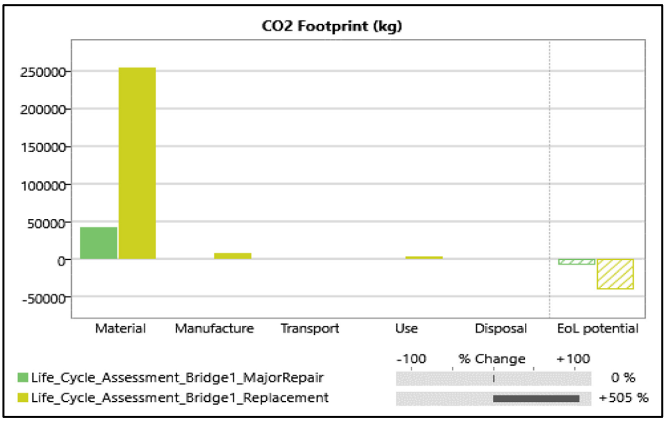

Fig. 6. Comparison of CO2 emission for major repair and replacement options.

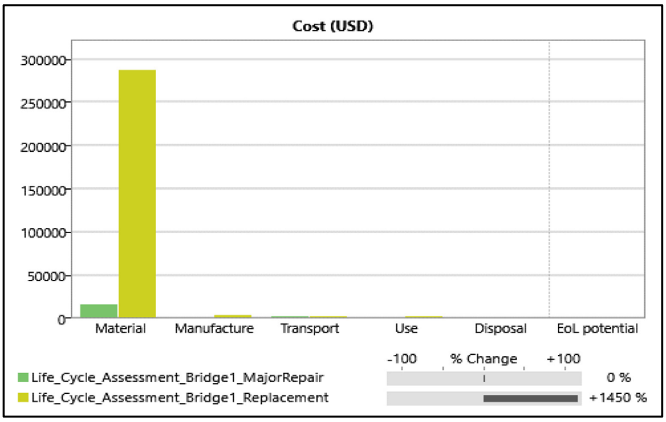

Fig. 7. Comparison of cost for major repair and replacement options.

4 Discussion of the results

A life cycle analysis was performed in this study to assess the performance of two rehabilitation strategies related to concrete bridge decks: major repair and replacement. The goal of the life cycle analysis was to determine the total energy, CO_2 emissions and the cost over the life (25 years) of the system. The total energy (J), the CO_2 emissions (kg) and the cost ($) of the main phases are related to material, manufacturing, transportation, use, and the end of life potential (Ghenai, 2012). These elements were determined using ECO Audit CES Edu pack software from Granta Design. The results of the life cycle analysis shown in Figures 3and 4 show the relative contributions of life phases (materials, manufacturing, transportation, use and end of life). The results of LCA for the bridge with the deck main repair (See Fig. 3) show that the main phase consuming more energy (95.1%), producing more carbon dioxide CO_2 (94.7%), and with the high cost (83.4%) is the material phase. The results of the Life cycle analysis for the bridge with the deck replacement (See Fig. 4) show that the material phase is the main phase that is consuming more energy (95.4%), producing more CO_2 emission (95.3%) and with the high cost (97.5%). A comparison of the total energy consumption, total carbon dioxide emission, and total cost for deck major repair and replacement options are shown in Table 7 and Figures 5-7. The total energy used and the carbon dioxide released to the atmosphere for the replacement option are respectively 5.76 and 6.05 times the one used for the bridge with the deck with major repair.

5 Conclusion

A life cycle analysis was performed in this study for the bridge deck using two rehabilitation strategies: major repair and replacement. The life cycle analysis results show clearly the benefits of using deck major repair compared to the deck replacement with respect to the life energy usage, CO_2 emisions and cost. The bridge deck replacement used 5.76 more energy and produces 6.05 more carbon dixide compared to the deck major repair. The second option with the bridge deck major repair is more sustainable, environmentally friendly and economically viable. Further future work is needed to assess the the major repair rehabilitation strategy with different materials.

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