Abstract

This report presents a comparative LCA analysis of two railway bridge superstructure with ballast track and concrete fixed track alternatives, the structure profile is based on the realistic design of Banafjäl bridge and new Åsta bridge in Sweden. The functional unit is defined as '1m railway bridge superstructure' including the track system, concrete slab and steel I girder structure, for 120 years life time. Several environmental impacts including the global warming potential, Eutrophication potential, Acidification potential and Ozone depletion Potential, Photochemical oxidation potential are assessed. The sensitivity analysis is carried out regarding the varied steel recycling rate in the end of life (EOL) stage. The purpose of this study is to compare the railway bridge with ballast track and fixed track alternative, thus determine the dominant structure components that contribute significant effects in the total environmental load. The result can be further implemented on other similar railway bridge type, and provide a basis to the administrator for further decision making and structure optimization. It has been found that the fixed track bridge has better environmental performance than the ballast bridge option in the total environmental impact through the whole life cycle.

1. Introduction

With the development of European high-speed railway network, the number of railway bridge infrastructure keeps an increasing growth annually. From which, the railway bridge system encounters new challenges of holding high speed and heavy traffic, meanwhile the requirement of environmental impacts must be fulfilled. There is a clear need to quantify and assign the environmental emissions into the impacts of humans and ecosystems. From the environmental perspective, the decisions made today may have a long-term effect for the whole life cycle of bridge. The railway bridge infrastructure has long life span and complex structural components, thus lead to tremendous material and energy consumption. Life cycle assessment (LCA) as a suitable holistic and systemic method for assessing the environmental impacts of a product or service through its whole life cycle, from 'cradle to grave', which is a comprehensive framework compiled with the ISO standards (ISO14040, 2006). The life cycle assessment can be applied for quantifying the environmental impacts linked with the bridge infrastructures, from the raw materials extraction, through the construction stage, use and operation stage, until the final demolish stage. It is possible to find some literatures for assessing the environmental impact associated with roadway bridges, but rare research has been done for railway bridges. Generally the principal for LCAs of roadway bridges can be applied for railway bridges as well; the major differences for those two infrastructures are in terms of the bridge track and the maintenance activities.

Life cycle assessment is a comprehensive framework for assessing environmental impacts of a product or service through its total life cycle (ISO14040, 2006). The term 'life cycle' refers to the sense that a holistic assessment of the product is performed from the raw material extraction phase, through manufacture phase, use phase until the final disposal phase, including all related transportation process, as presented in Figure 1.

The methodology of LCA is standardized by the ISO 14040 and ISO14044 series guidelines, it includes four phases: Goal and Scope phase, life cycle inventory phase, life cycle impact assessment phase, and result interpretation (ISO14040, 2006):

Goal Definition and Scoping phase is the process to define the boundaries and purpose of the study, identify environmental effects to be reviewed for the assessment.

Inventory Analysis phase is to input the material flow and energy into the defined study system, thus obtain the environmental releases including air emissions, solid waste disposal, waste water discharges.

Impact Assessment phase is to assess the environmental loading and impact categories by characterization, normalization, weighting and grouping procedure, on the basis of inventory analysis results.

Interpretation phase is to explain and present the results of the inventory analysis phase and impact assessment phase to make a fair and clear result, identify the uncertainty and assumptions of the study.

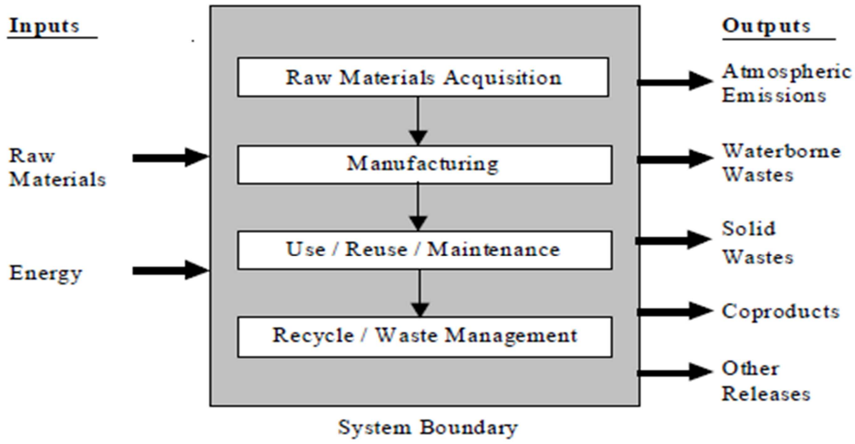


Figure 1: Life cycle stages (EPA, 1993&2006)

2. Case study of the Banafjäl Bridge

2.1 Project background

The Banafjäl Bridge is a 42 meters high speed railway bridge located on the Bothnia line in Sweden, the superstructure section is comprised of a reinforced concrete deck and two steel I-girder beams. The concrete slab is made of concrete quality C32/40 according to the Eurocode, supported by two 2.5 meters high steel I-beams, made of steel S460M at flange and steel S420M at web panel (Guillaume, 2010). In order to assess the environmental performance of the Banafjäl Bridge, two alternative railway superstructure systems of ballast and fixed slab railway track was studied by attributional LCA model in Simapro. The ballast single track solution is originally designed for the Banafjäl Bridge as presented in Figure 3, while the fixed slab track option is modified from the realistic design of New Åsta Bridge, a ten span prestressed concrete railway bridge with fixed-slab double track system, as presented in Figure 4. The New Åsta Bridge fixed-track system is further adjusted to the single track dimension in Banafjäl Bridge. The steel I-beam of Banafjäl Bridge has been redesigned both for the ballast and non-ballast condition by Guillaume (2010).

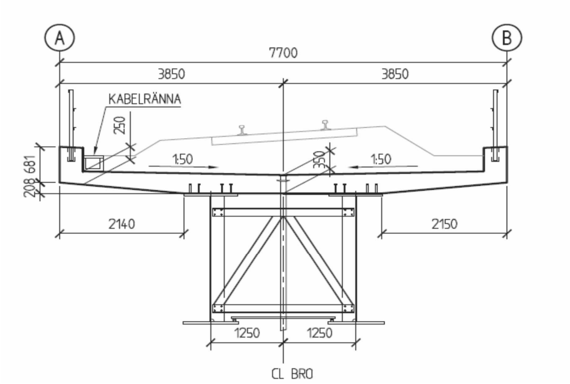


Figure 3: Banafjäl Bridge designed with ballast track

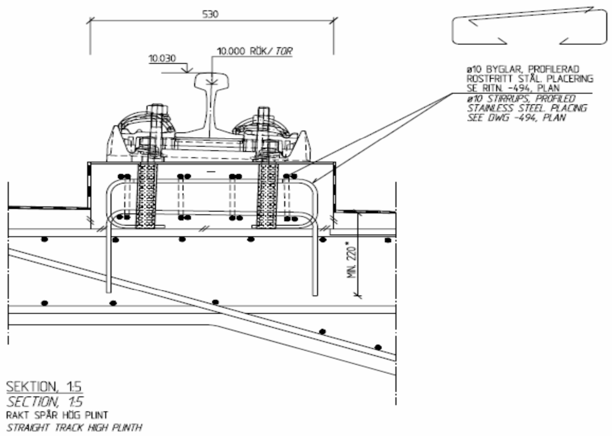


Figure 4 Banafjäl Bridge designed with fixed slab track

2.2 Goal of the study

Currently there are mainly two types of railway track system widely used in the railway bridge infrastructure: ballast track and fixed-slab track, both of which have advantages in different technical aspects. The ballast railway bridge as a traditional type is widely used in Sweden, it has an advantage in the noise reduction, water absorption, and low initial construction costs (C.K. Lee, et. al., 2008). While the fixed slab track has benefit in the ease construction process, free maintenance and low operational cost. In this paper the comparative LCA is applied for analyzing the environmental impact of two railway bridge systems: the ballast track bridge and the fixed-slab track bridge. The goal is to compare the environmental impact of two bridge alternative design through the whole life cycle, from 'cradle' to 'grave', thus identify the dominant structural components and the key life cycle stages that contribute the significant environmental impact. The material reuse and recycling at the end of the life cycle are suspected to contribute the benefit in the life cycle. The final analysis result could be implemented into other similar bridge design option, providing a preliminary basis for further detailed assessment and optimization.

2.3 Functional unit

Based on the Swedish bridge standards (BVS 583.10, BV Bro 2004), the railway bridge is designed with 120 years' service life. However, the real life span varies due to the specific project and technical design criteria. In order to compare two bridge systems and simplify the material flow calculation for the LCA analysis of the Banafjäl Bridge, the functional unit based on the same measurement scale is defined. Thus for the two alternative designs of ballast track and fixed slab track for Banafjäl Bridge with 42 m length: the functional unit is defined as within the life span of 120 years, 1 meter length of bridge superstructure in the longitudinal direction for serving the function of the annual traffic volume. The traffic volume for the Bothnia line in 2020 is predicted by the Swedish Railway administration Office, as presented in Table 1.

Table 1. Traffic forecast for the Bothnia Line in 2020. (Freight transport, Botniabanan AB, 2010)

Train type	Annual transport in passenger km (pkm) and tone km (tkm)
Passenger	343800000 pkm
Freight	506400000 tkm

2.4 System boundaries

The railway bridge infrastructure consists of two parts: railway track and bridge main body. Since the design of bridge main body keeps identical in both alternative designs, thus only the superstructure of the bridge are chosen for study in this paper, including railway track, bridge slab and steel I girder-beams. The LCA analysis is carried out for the whole life cycle of the bridge superstructure, from the construction phase, though use and maintenance phase, until the end of life. Figure 2 presented the life cycle stages and system boundaries for the study. Due to lack of data, the electricity consumption and the labor work through the life cycle are excluded in the scope. The structure components of rubber pad, parapet, and expansion joints, which were proved have insignificant environmental impact in previous literatures, are also excluded from the scope.

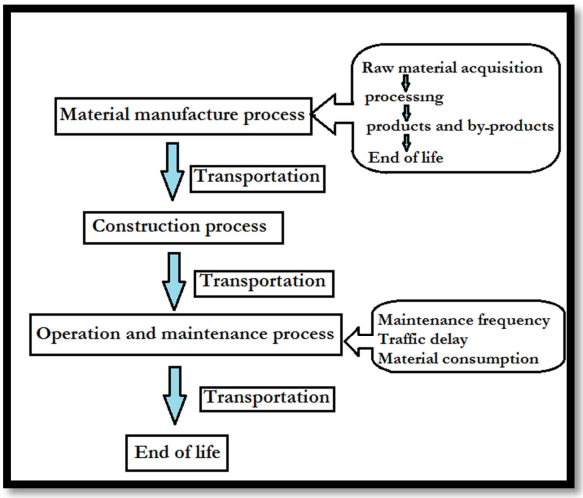


Figure **2** Life Cycle Assessment stages and system boundaries

2.5 Methodology

The CML 2001 (baseline) method is applied in the LCA analysis of two bridge alternative designs, from which the impact indicators are oriented at 'mid-point' level. Several impact categories are taken into account in the analysis, including Global warming Potential (GWP), Ozone depletion Potential (ODP), Photochemical Oxidation Potential

(POCP), Acidification Potential (AP), Eutrophication Potential (EP), etc. All results categories are related to the functional unit of 1 m bridge superstructure through the 120 years' life time.

2.5.1 Characterization

The purpose of characterization process is to aggregate the LCI emissions to describe the corresponding caused environmental effects. Henrikke and Anne (2004) illustrated that the complexity of environmental systems lead to certain impact categories having several alternative characterization models. In this paper, the characterization of LCI emissions for each construction material is performed by using CML (2001) characterization factors, referring to the 'mid-point' level and several impact categories under study are presented in Table 3.

2.5.2 Normalization

The normalization results can relate the environmental impact results to the actual magnitude of the referred geographical area, thus obtain a comprehensive knowledge of the realistic caused effect from the infrastructure. The normalization factors in this paper are obtained from CML (2001) which the representative area is referring to Europe, as presented in Table 3.

2.5.3 Weighting

The weighting process emphasized the relative importance of each impact category by weighting factor, thus to obtain a summed score, as presented in Table 3. In this paper, the EPA weighting factors (Brattebø H., et. al., 2009) is applied for the environmental assessment of two bridge alternative.

Table 3. CML (2001) normalization factors

		Normalization factor	Weighting factor
Impact category	Unit		
Abiotic depletion	kg Sb eq/yr	1.71E+09	5
Acidification	kg SO2 eq/yr	6.71E+08	5
Eutrophication	kg PO4--- eq/yr	5.03E+08	5
Global warming	kg CO2 eq/yr	2.53E+11	16
Ozone layer depletion	kg CFC-11eq/yr	9.80E+05	5
Photochemical oxidation	kg C2H4/yr	1.82E+08	6

2.6 Assumptions and limitations

Assumption of transportation: The material transportation largely depends on the material type and price fluctuation. For the purpose of simplification, the idealized assumption is made by that the material in the same type are transported by the same distance. The transportation distances are counted from manufacture factory to the construction site. For instance, the ballast and all structural components made by concrete are purchased from nearby village Ovik within 30km distance, and the steel and reinforcement are transported from Sundsvall within 100km, the long distance transportation of those material are by using truck lorries.

Assumption of maintenance and EOL scenarios: the bridge infrastructure has a long life cycle, the future increased machinery efficiency and traffic growth may affect the eventual environmental impact, however, the current maintenance and EOL scenarios are assumed based on previous project experiences, thus involved a high level uncertainties.

Uncertainty of inventory data: the LCI data is the most uncertain factor for the LCA analysis, Mark A. J. H., (2001) illustrated two critical reasons for the uncertainties of LCI database: a lack of representative data and data inaccuracy.

Usually the global average LCI database is applied in the LCA analysis, which leads to a data gap from the real product suppliers.

3. Life cycle assessment of Banafjäl Bridge

3.1 Material manufacture phase

The material manufacture process is the most complex phase through the whole life cycle of the bridge, which itself build up a complete life cycle. The environmental emissions generated from this process are known as the indirect embodied emissions (R.H.Crawford, 2009). The commercial LCI database provides the complete environmental profile of different materials for the average value in Europe, including the full manufacture life cycle and the transportation processes.

3.2 Construction phase

According to the defined system boundary of Banafjäl Bridge, the material and energy inputs of each structural element and system is accounted, with the consideration of transportation process from manufacture site till the construction site, as well as the building machinery energy consumptions. The selected structure elements and processes in the assessment are those contribute relatively high proportions to the bridge function. The material quantities of bridge span could be obtained from the realistic design sketch.

3.2.1 Bridge Deck system

Reinforced concrete slab The reinforced concrete slab of Banafjäl bridge is designed identically for both track alternative, with a curvature radius of 4000 m, and the concrete slab thickness varies from 250 mm to 400 mm. Both the quantity of the concrete and the reinforcement are calculated based on the realistic design drawing manual as in Figure 1. On the basis of realistic design as showed in Figure 5 and Table 4, total amount of 6280 kg/m concrete and total amount of 347kg/m reinforcement including longitudinal reinforcement, transversal reinforcement and stirrups within 1 meter are obtained.

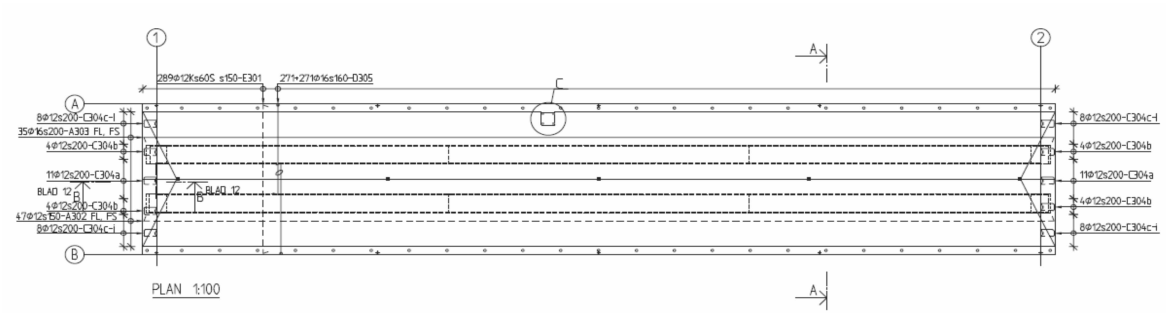


Figure 5: the reinforcement design of concrete slab

Table 4: the reinforcement quantity of the concrete slab

	Banafjäl bridge superstructure of bridge				
	Main beam	no.	Ø (mm)	length (m)	kg
Longitudinal reinforcement	8Ø12s200-C304c-1	16	12	2.45	34.8096
	35Ø16s200-A303	35	16	42	2321.13
	4Ø12s200-C304b	8	12	2.45	17.4048
	11Ø12s200-C304a	22	12	2.45	47.8632
	4Ø12s200-C304b	8	12	2.45	17.4048
	47Ø12s150-A302	47	12	42	1752.912
	8Ø12s200-C304c-1	16	12	2.45	34.8096
Transversal reinforcement	289Ø12Ks60S s150-E301	289	12	7.7	1976.066
	271+271Ø16s160-D305	542	16	7.7	6589.799
	Edge beam	no.	Ø (mm)	length (m)	kg
	10Ø16-A308	10	16	42	663.18
Stirrups	217Ø12s200-EX307	217	12	1.7	328.0649
	217Ø12s200-EX306	217	12	1.7	328.0649
	600Ø22	600	22	0.175	404.775
sum					14516.28
Per meter					346 kg/m

Steel section The steel section is divided into three segments along the whole bridge with various dimensions. In order to simplify the calculation, the average dimension is applied in the LCA model. Figure 5 presented the steel cross section Gillet (2010) has redesigned the bridge steel section both for ballast and fixed slab track, the dimension of the two steel section alternatives are presented in Table 5. Based on the statistic design calculation of the steel-concrete composite beam performed by Gillet (2010), the mass of the steel section for fixed slab track is 1815 kg/m and for ballast track is 2139 kg/m, which was increased by 15%.

Painting In order to protect the steel I girder section corrosion from the atmospheric, the polyurethane coating and zinc epoxy coating layer are provided over the whole steel surface. Normally chromium and lead are contained in the painting, thus cause significant environmental effects. The painting surface area for ballast and fixed-slab track alternative is calculated as 13.74 m2/m and 13.55 m2/m xylene respectively, on the basis of section design by Gillet (2010), the dimension of the two alternatives are presented in Table 4.

Table 5: steel section dimension

		b_u (mm)	hw (mm)	t_w (mm)	t_1 (mm)	b_1 (mm)	m^2/m
Ballast track	48	900	2397	17	55	950	13.7
Fixed slab track	46	900	2409	14	45	900	13.5

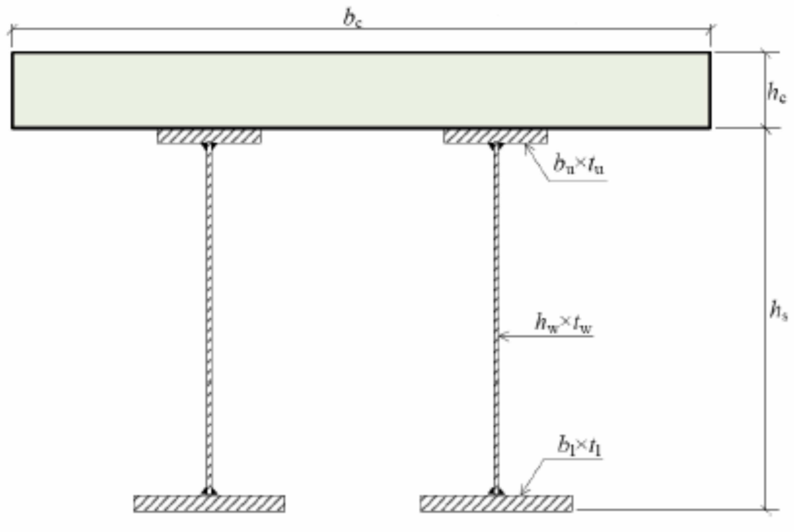


Figure 5 Simplified cross section of steel I beam in Banafjäl Bridge

4.2.2 Railway track system

Rail: The Swedish railway administration currently uses UIC60 profile, which is the most common used rail type in Europe, with steel quality R260 and R350LHT(Peter N and Johan G., 2008). For both ballast track and fixed-slab track alternative, the continuously welded UIC 60 single rail track is applied, the mass quantity within 1 meter is 60*2kg/m=120 kg/m, modeled by chromium steel 18/8 in SimaPro, considering the hot metal transportation, steel manufacture process and casting.

Ballast For the ballast system option, the ballast is modeled by crushed stone material, with the geometry simplified to a rectangular of 6.9 m wide by 0.6m high, the weight density 20 kN/m^3 (Collin, P et al., 2008). Thus the ballast mass within 1 meter is 6.9m*0.6m*42m*2000kg/m3/42m=8.3 ton/m.

Sleepers The sleeper is made by the reinforced concrete block for both track alternatives. For ballast track, the sleeper is dimensioned as 0.2*0.2*2.5m^3, according to the Rail Administration's requirement of sleeper, each sleeper weighted around 300 kg, separated by spacing 60 cm (Peter N and Johan G., 2008). Thus within 1 meter, the concrete quantity of the ballast track is 0.2*0.2*2.5*(1/0.6) = 0.17 m3/m, modeled by normal concrete. And the reinforcement is 10.16 kg/m as presented in Stripple (2010). For the Fixed-slab track system, the quantity of the concrete and reinforcement are 0.091 m3/m and 14.8 kg/m respectively, obtained from the realistic design manual, as presented in Figure 6.

Fastening clip The Swedish railway administration mostly use Pandrol fastening system (Peter N and Johan G., 2008), thus both ballast and fixed-slab track are modeled by the Pandrol fastening clip. Pandrol manufactures a range of rail fastenings with the typical weight of 15mm diameter; the total weight of each fastening clip combined with a toe insulator is 620g (personal communication). For the Banafjäl bridge track, the fastening clip is 0.62kg*4*42/0.6/42=4.13kg/m, modeled by the stainless steel material.

Transportation process: The emission and energy consumption caused from transportation process is also modeled in SimaPro, from the material manufacture gate to the construction site. Two transportation methods is modeled: truck fleet average lager than 16t and ship barge tanker. It is assumed all the concrete are transported from nearby city Övik within 30 km distance by truck, the steel and reinforcement are purchased from city Sundsvall within 100 km by truck, and the ballast are transported from 200km by ship barge tanker, as presented in Table 6.

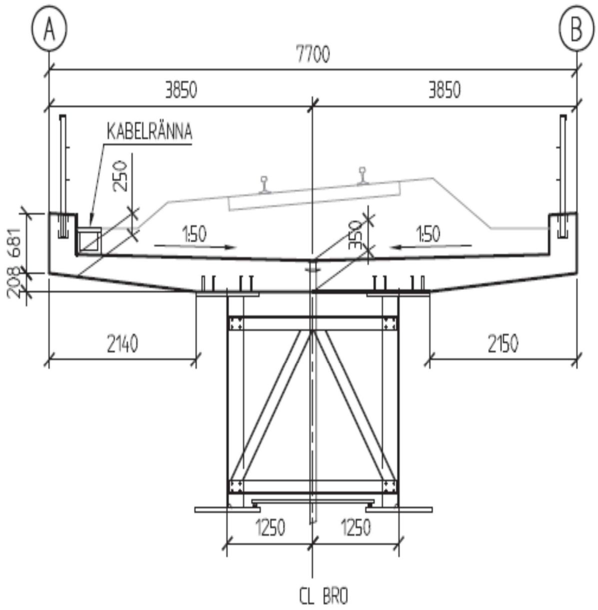


Figure 6 the design of the Banafjäl Bridge

Table 6 Transportation process of construction material

item	transportation	Ballast track bridge	Fixed-slab track bridge
Ballast	30 km by truck	249 tkm	0
Concrete	30 km by truck	200 tkm	194 tkm
Steel and reinforcement	100 km by truck	261 tkm	229 tkm
Total truck transportation		710 tkm	423 tkm

Energy consumption: Both diesel and gasoline consumption during the construction stage are considered in the model. The assumption of consumed quantity is made on the basis of Lee. et al. (2008), it has been found the diesel and gasoline consumption during construction for a 30 km ballast track is 376 L and 25 L, while for the same length fixed slab track is 33.9 L and 10 L. Therefore, the diesel and gasoline consumption for both bridge alternatives is assumed as in Table 7.

Table 7: the energy consumption of ballast track and fixed slab track during construction

	Ballast track bridge	Fixed slab track bridge
Diesel consumption (L/m)	12.5	1.13
Gasoline consumption (L/m)	0.84	0.33

4. LCI of Banafjäl Bridge

The life cycle inventory (LCI) analysis is performed for the two alternative design options of the Banafjäl Bridge: ballast bridge and fixed slab bridge. The studied bridge superstructure in each option consists of bridge deck system and railway track system, several LCI databases are applied for obtaining the global environmental impacts of each construction material. Table 8 presents the detailed sub-structural components of the bridge and the corresponding

LCI database. The inventory data of material quantities, energy consumption and transportation process are collected based on the realistic design drawings and recorded project information.

Table 8: Material summary for two bridge design alternative

		Ballast track alternative	Fixed track alternative	Service life	Type of data	Database
Bridge deck system	Reinforcement	346kg/m	346kg/m	N/A	Reinforcing steel, at plant/RER U	Ecoinvent
	Concrete slab	6280 kg/m	6280 kg/m	N/A	Concrete, sole plate and foundation, at plant/CH U	Ecoinvent
	Steel section	2139 kg/m	1815 kg/m	N/A	Steel hot rolled section, blast furnace and electric arc furnace route, producti	ELCD 2.0
	Painting	13.74 m2/m	13.55 m2/m m2/m	30 years	Automotive painting, top coat, per m2/m2/RNA	U.S. LCI Database
track system	Rail	120 kg/m	120 kg/m	25 years	Steel, converter, chromium steel 18/8, at plant/RER S	Ecoinvent
	Ballast	8.3 ton/m	-------	20 years[1]	Crushed stone 16/32, open pit mining, production mix, at plant, undried RER S	ELCD 2.0
	Concrete of sleepers	0.17 m3/m	0.091 m3/m	50 years [1]	concrete, normal, at plant/m3/CH	Ecoinvent
	Reinforcement of sleepers	10.16kg/m	14.8 kg/m	50 years [1]	Reinforcing steel, at plant/RER U	Ecoinvent
	Fastening clip	4.13kg/m	4.13kg/m	25 years	Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 304 RER S	ELCD 2.0

5. Use and maintenance phase

Maintenance phase takes the longest duration through the whole life cycle of the bridge infrastructure, which requires regular material and machinery energy consumption. The railway bridge maintenance interval is dominated by the designed service life, train load, traffic volume and regular inspection results. However, it is critical to make reasonable assumptions for the maintenance scenarios and the corresponding intervals, which would affect the final results. Based on previous project experience, a series maintenance activities and repair intervals are presented in Table 9. It is assumed that for the maintenance of each structural element, the amount of raw material is the same as consumed in the construction phase.

[1] For ballast track system, no ballast and sleeper replacement for the slab track system

Table 9 The maintenance activity during the whole life cycle

Structure element	Maintenance activity during 120 years service life	Ballast track	Slab track
Railway track	Rail grinding	1 year	1 year
	track direction Ballast tamping	0.5 year	-----
	Rail replacement[2)]	25 years	25 years
	Sleeper renewal	50 years	-----
	Fastener renewal[3)]	25 years	25 years
	Ballast renewal	20 years	-----
Steel beam	Repainting	30 years	30 years

6. End of life

The waste material will benefit the environmental impact if treated properly, meanwhile considerable energy consumption and transportation processes are involved in the waste treatment process. At the EOL stage, the bridge will be demolished and thus several waste scenarios are modeled for the material waste treatment. The main construction material for the railway bridge is steel and concrete. Steel is recyclable and the scrap can be converted to the same (or higher or lower) quality steels. Michael D. Fenton (1998) compared the annual tonnage of steel used to produce the new product with the tonnage of recycled product, it has been found the steel recycling rate for the construction plate and beams is 88%. In SimaPro, the benefit of steel recycling are allocated to the manufacture of new steel product by the recycled iron. From which, 1 kg pig iron is used as avoided product and 1 kg scrap iron is used as input from technosphere for modeling the scenario of 1 kg steel recycling. The steel EOL is modeled by 88% recycling process and 12% landfill. The waste scenario for concrete is modeled by concrete gravel landfill, that including the energy consumed from dismantling, particular matter emissions for dismantling, transportation and final disposal. The total quantity of concrete and steel of two railway track alternatives for the Banafjäl Bridge is calculated and presented in Table 11.

Table 11: Quantity of concrete and steel for waste scenario

	Ballast railway bridge	Fixed track railway bridge
concrete total amount kg	6680	6499
steel total amount kg	16785	16466

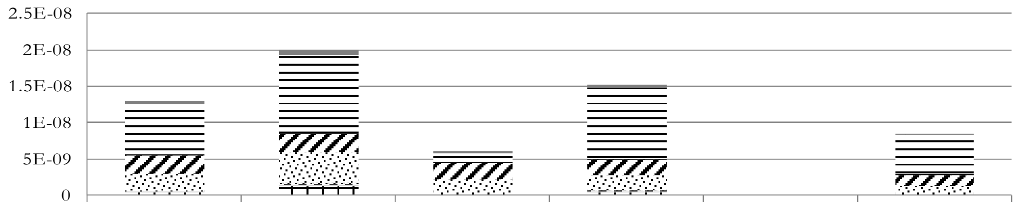
7. Result presentation

The environmental impact assessment is carried out by using the SimaPro software, where six environmental impact categories are presented in Table 3. The final results are presented into three parts: i) the environmental impact regarding the allocation of each structural element during the construction phase and the use phase; ii) the comparison between two bridge design options in each life stage iii) the aggregated environmental impacts for each bridge option through the whole life cycle.

7.1 Environmental allocation of each structural element

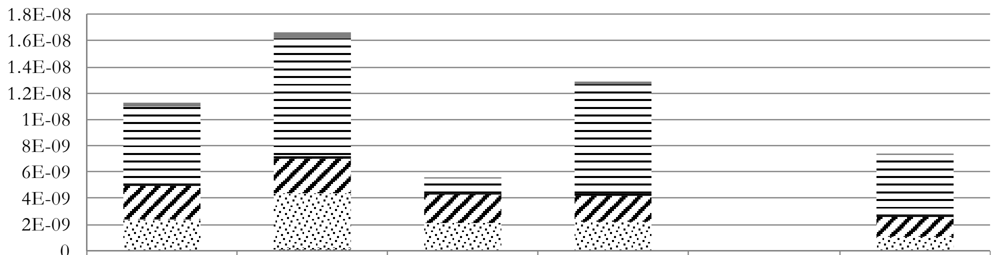
Regarding the environmental contribution of each structural element during the construction phase, Figure 7 presents the normalized results for two bridge alternatives. It has been found that for both bridge alternative, the main source of impact burden is associated with the manufacture of steel I girder, reinforced concrete slab and the rail UIC60 element. The reason is due to the large material consumption of those structural elements as well as the high embodied LCI emission of the steel material.

Ballast bridge construction phase



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
truck transportation	4.014E-10	7.65019E-10	2.70973E-10	3.74578E-10	1.55207E-11	8.42758E-11
Steel I girder for ballast track	6.99116E-09	1.05252E-08	1.27487E-09	9.75198E-09	0	5.4105E-09
sleeper for ballast track	1.31593E-10	1.88594E-10	1.01037E-10	2.35052E-10	2.09243E-12	6.03395E-11
reinforced concrete slab	2.55451E-09	2.62712E-09	2.18896E-09	2.01934E-09	1.97517E-11	1.54187E-09
rail UIC60	2.3275E-09	4.17539E-09	2.11006E-09	2.11715E-09	2.31123E-11	1.01414E-09
painting 1 m2	4.11186E-11	1.38058E-10	6.61132E-12	3.96258E-11	8.25517E-17	4.55371E-11
gasoline consumption (1liter)	9.03898E-12	2.86818E-11	7.89119E-12	9.14595E-12	8.67417E-17	1.98427E-11
fastening clip	3.178E-11	1.14588E-10	8.83099E-12	5.55311E-11	0	1.95108E-11
Diesel consumption (1 liter)	1.5111E-10	1.57127E-10	1.96864E-11	1.58527E-10	1.45011E-15	4.56085E-11
Ballast	3.83103E-10	1.29558E-09	1.16814E-10	4.58101E-10	2.2301E-11	1.85696E-10

Fixed slab bridge construction phase

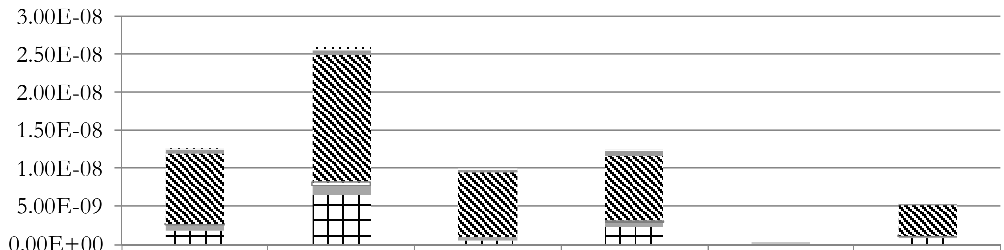


	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
truck transportation	2.39144E-10	4.55779E-10	1.61439E-10	2.23164E-10	9.24681E-12	5.02094E-11
steel I girder for fixed slab track	5.93219E-09	8.93096E-09	1.08176E-09	8.27482E-09	0	4.59096E-09
sleeper for fixed slab track	1.39549E-10	1.72018E-10	1.13304E-10	1.80438E-10	1.65426E-12	7.40142E-11
reinforced concrete slab	2.55451E-09	2.62712E-09	2.18896E-09	2.01934E-09	1.97517E-11	1.54187E-09
rail UIC60	2.3275E-09	4.17539E-09	2.11006E-09	2.11715E-09	2.31123E-11	1.01414E-09
painting 1 m2	4.055E-11	1.36149E-10	6.5199E-12	3.90779E-11	8.14102E-17	4.49074E-11
gasoline consumption (1liter)	3.55103E-12	1.12679E-11	3.10011E-12	3.59305E-12	3.40771E-17	7.79534E-12
fastening clip	3.178E-11	1.14588E-10	8.83099E-12	5.55311E-11	0	1.95108E-11
Diesel consumption (1 liter)	1.36059E-11	1.41477E-11	1.77256E-12	1.42738E-11	1.30568E-16	4.10658E-12

Figure 7 Normalized result of structural elements allocation during construction phase

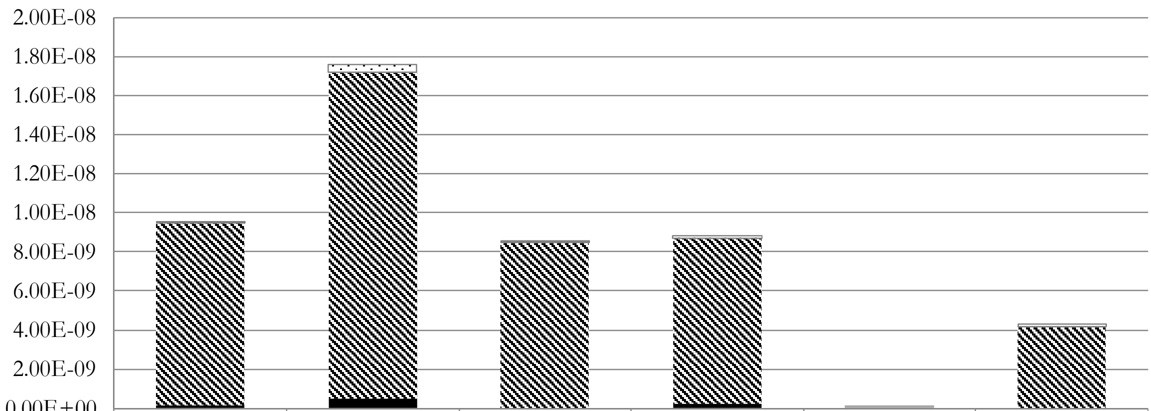
For the environmental contribution of regular maintenance activities during the use phase, Figure 8 presents the normalized results for the two bridge alternatives. Compare to the ballast bridge, the railway track of fixed slab bridge is deemed as maintenance free, the excluded maintenance activities including sleepers, ballast and corresponding transportations. The rail UIC60 replacement contribute the most significant environmental impact for both bridge alternatives; while for the ballast bridge alternative, the ballast maintenance is the main concern for the total environmental impact.

Ballast bridge maintenance phase



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
painting 1 m2	1.23E-10	4.14E-10	1.98E-11	1.19E-10	2.48E-16	1.37E-10
truck transportation	2.03E-11	3.86E-11	1.37E-11	1.89E-11	7.84E-13	4.26E-12
sleeper for ballast track	3.95E-10	5.66E-10	3.03E-10	7.05E-10	6.28E-12	1.81E-10
truck transportation	5.43E-12	1.03E-11	3.66E-12	5.06E-12	2.10E-13	1.14E-12
rail UIC60	9.31E-09	1.67E-08	8.44E-09	8.47E-09	9.24E-11	4.06E-09
fastening clip	1.27E-10	4.58E-10	3.53E-11	2.22E-10	0.00E+00	7.80E-11
truck transportation	7.04E-10	1.34E-09	4.75E-10	6.57E-10	2.72E-11	1.48E-10
Ballast	1.92E-09	6.48E-09	5.84E-10	2.29E-09	1.12E-10	9.28E-10

Fixed slab bridge maintenance phase

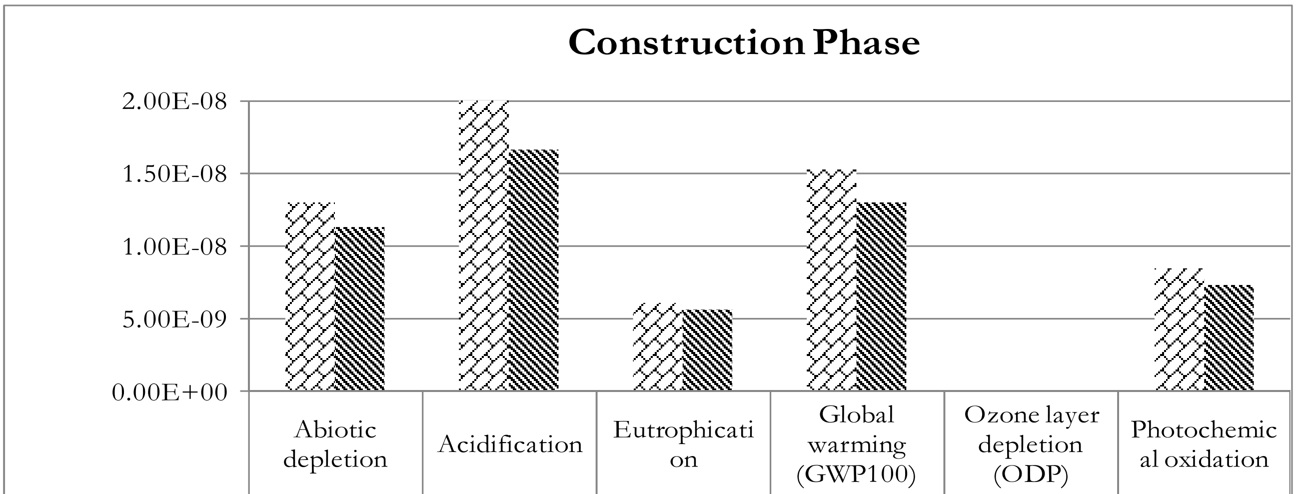


	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
painting 1 m2	1.22E-10	4.08E-10	1.96E-11	1.17E-10	2.44E-16	1.35E-10
truck transportation	5.43E-12	1.03E-11	3.66E-12	5.06E-12	2.10E-13	1.14E-12
rail UIC60	9.31E-09	1.67E-08	8.44E-09	8.47E-09	9.24E-11	4.06E-09
fastening clip	1.27E-10	4.58E-10	3.53E-11	2.22E-10	0.00E+00	7.80E-11

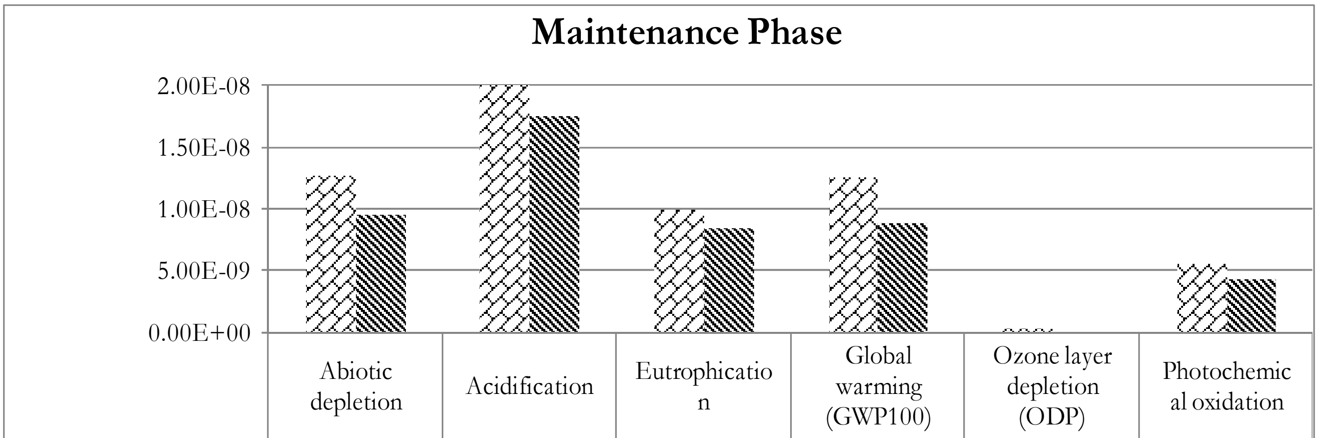
Figure 8 Normalized result of structural elements allocation during maintenance phase

7.2 Comparison between the two bridge alternatives

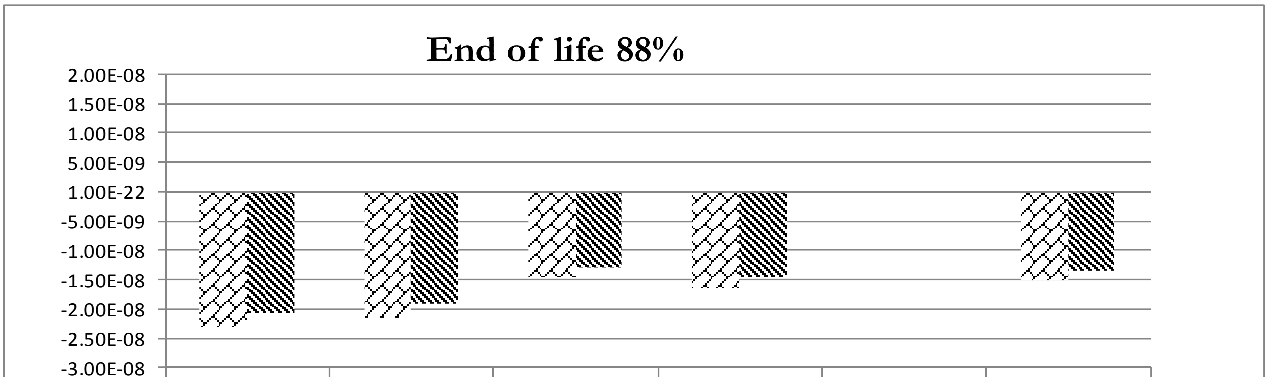
The relative environmental impact comparison between the ballast bridge and the fixed slab bridge are presented in Figure 9, which indicate the normalized result for the whole life cycle of the construction phase, maintenance phase and end of life. For the construction phase and the maintenance phase, the fixed slab bridge shows a better environmental performance in all impact categories. The most important categories are the global warming potential and the acidification potential, the ozone layer depletion potential cause the negligible impact. In the EOL stage, it shows an opposite trend, the ballast bridge accounts for a greater share in the negative contribution, which indicates the material recycling of ballast bridge provides a larger saving than the fixed slab bridge, due to more steel consumptions during the construction and maintenance stage. The material recycling in the EOL stage performs a preferable impact to the society. The harmful impact is presented as a positive value in the construction and maintenance chart, while the benefit impact in the EOL phase is presented as a negative value.



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
ballast bridge	1.30E-08	2.00E-08	6.11E-09	1.52E-08	8.28E-11	8.43E-09
fixed slab bridge	1.13E-08	1.66E-08	5.68E-09	1.29E-08	5.38E-11	7.35E-09



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
ballast bridge	1.26E-08	2.60E-08	9.88E-09	1.25E-08	2.38E-10	5.53382E-09
fixed slab bridge	9.56E-09	1.76E-08	8.50E-09	8.81E-09	9.27E-11	4.27047E-09



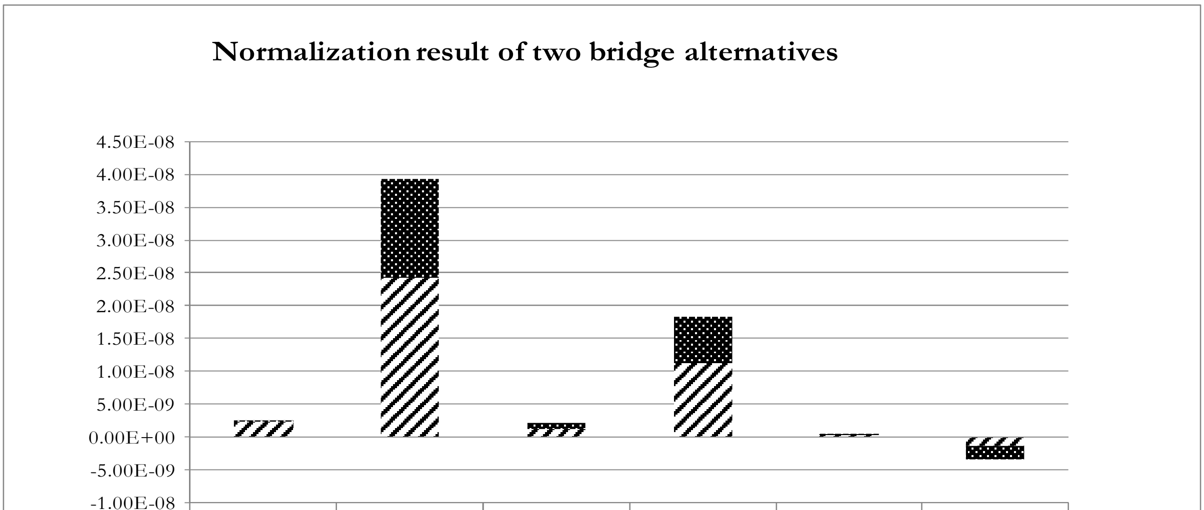
	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
ballast bridge	-2.33E-08	-2.17E-08	-1.48E-08	-1.65E-08	-6.15E-11	-1.53E-08
fixed slab bridge	-2.07E-08	-1.93E-08	-1.31E-08	-1.47E-08	-5.47E-11	-1.36E-08

Figure 9 Environmental comparisons between two bridge alternatives through the whole life cycle

7.3 Aggregated results

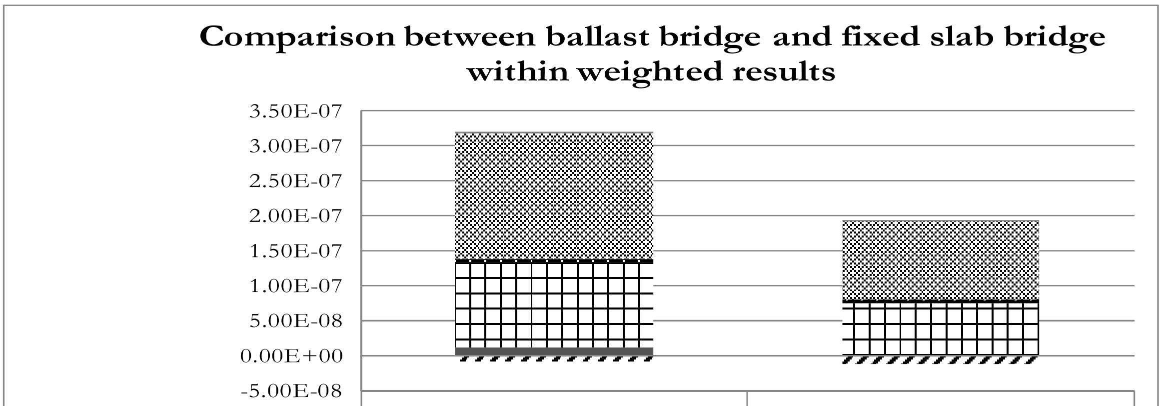
The normalized result in Figure 10 shows the comparison between two bridge alternatives, it has been found that the fixed slab bridge exhibits the best environmental impacts among all impact categories. The ease maintenance process during the use and operation phase is accounted for the main reason.

The importance of six environmental impacts is evaluated by the EPD weighting factors, as presented in Table 3. All mid-point environmental impact categories are integrated into a single score, the final result is presented in Figure 11, which shows the fixed slab bridge option performs the preferable environmental impact, with the emphasize of global warming potential as the most important category.



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
Fixed slab bridge	1.21E-10	1.49E-08	1.03E-09	7.05E-09	9.17E-11	-1.98E-09
Ballast bridge	2.30E-09	2.43E-08	1.19E-09	1.12E-08	2.60E-10	-1.33E-09

Figure 10 The normalized result for two bridge alternatives

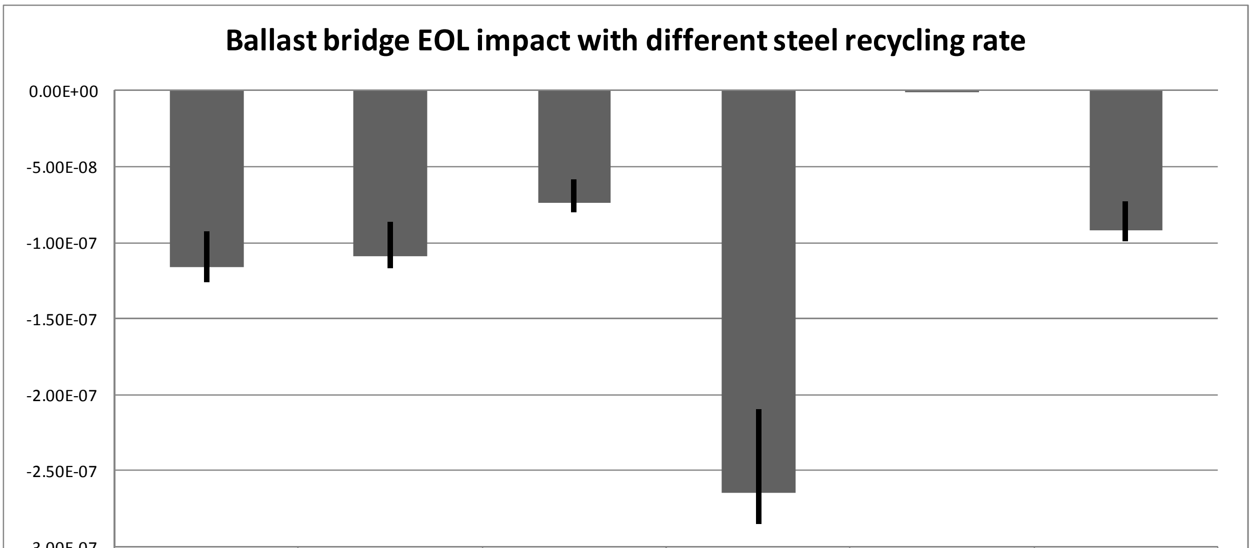


	Ballast bridge	Fixed slab bridge
Photochemical oxidation	-8.01E-09	-1.19E-08
Ozone layer depletion (ODP)	1.30E-09	4.59E-10
Global warming (GWP100)	1.79E-07	1.13E-07
Eutrophication	5.97E-09	5.16E-09
Acidification	1.21E-07	7.45E-08
Abiotic depletion	1.15E-08	6.05E-10

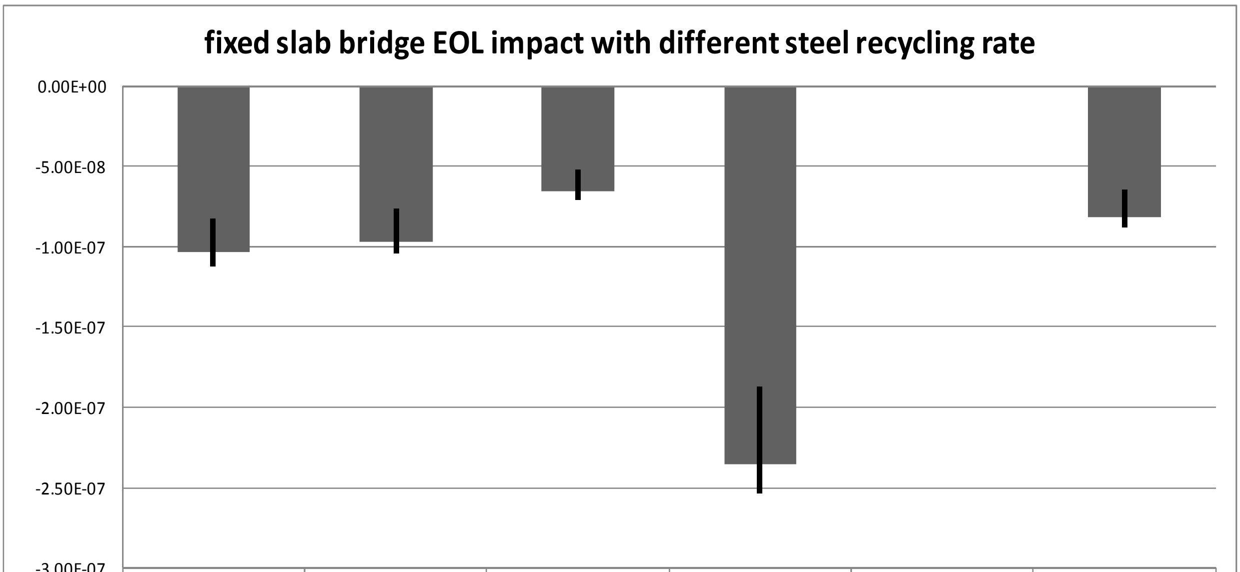
Figure 11, the comparison of two bridge alternatives within weighted results

7.4 Sensitivity analysis

The bridge infrastructure is a complex system involves various structural components and scenarios. The assumption of life cycle scenarios may highly affect the total environmental impact. This paper performed the sensitivity analysis for the two bridge alternative regarding different steel recycling rate varies from 70%, 88% to 95%. As presented in Figure 12, the positive impact due to the steel recycling increases with the increased steel recycling rate for both bridge alternatives. The steel recycling has the highest benefit for the global warming category among all the other categories.



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
EOL 88%	-1.17E-07	-1.09E-07	-7.39E-08	-2.64E-07	-3.08E-10	-9.18E-08
EOL 70%	-9.26E-08	-8.62E-08	-5.87E-08	-2.10E-07	-2.38E-10	-7.30E-08
EOL 95%	-1.26E-07	-1.17E-07	-7.98E-08	-2.86E-07	-3.35E-10	-9.91E-08



	Abiotic depletion	Acidification	Eutrophication	Global warming (GWP100)	Ozone layer depletion (ODP)	Photochemical oxidation
EOL 88%	-1.04E-07	-9.66E-08	-6.57E-08	-2.35E-07	-2.73E-10	-8.16E-08
EOL 70%	-8.23E-08	-7.66E-08	-5.22E-08	-1.87E-07	-2.11E-10	-6.49E-08
EOL 95%	-1.12E-07	-1.04E-07	-7.10E-08	-2.54E-07	-2.98E-10	-8.81E-08

Figure 12 Sensitivity analyses regarding different steel recycling rate

8. Conclusions

This paper presented a comparative LCA analysis of two bridge alternatives during 120 years service life: fixed slab bridge and ballast bridge. The proposed design of the two bridge alternatives are based on the realistic bridge: the Banafjäl bridge and the New Åsta bridge. The study considers all the key stages through the life cycle of materials manufacture, construction, maintenance, and EOL. The environmental contribution of each structural element in a bridge infrastructure was analyzed. The result shows that the fixed-slab bridge contributes less environmental impact in the total environmental impact, due to the optimal structure form and ease maintenance strategies. The usage of the steel products such as I girder, the rail track and reinforcement account for a large proportion of environmental impacts, meanwhile, the corresponding steel recycling increased the environmental benefits. The technical structure form of the infrastructure plays an important role for the associated environmental impact. The recycling rate and waste scenario assumptions in the EOL phase has significant effect for the total environmental burden.

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