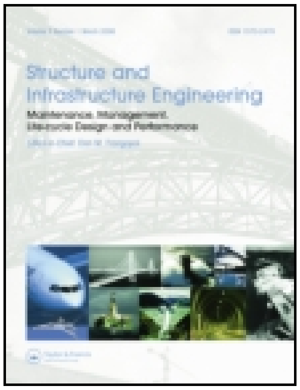
Life cycle assessment of a railway bridge: comparison of two superstructure designs

Du, Guangli; Karoumi, Raid

Published in:
Structure & Infrastructure Engineering

DOI (link to publication from Publisher):
10.1080/15732479.2012.670250

Publication date:
2013



Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/nsie20

Life cycle assessment of a railway bridge: comparison of two superstructure designs

Guangli Du [a] & Raid Karoumi [a]
[a] KTH Royal Institute of Technology, Division of Structural Engineering and Bridges , Brinellvägen 23, Stockholm , 10044 , Sweden
Published online: 29 Mar 2012.

Structure and Infrastructure Engineering
Vol. 9, No. 11, November 2013, 1149–1160

Life cycle assessment of a railway bridge: comparison of two superstructure designs

Guangli Du* and Raid Karoumi

KTH Royal Institute of Technology, Division of Structural Engineering and Bridges, Brinellvägen 23, Stockholm 10044, Sweden

(*Received 11 July 2011; final version received 17 January 2012; accepted 18 January 2012; published online 29 March 2012*)

Railway bridges currently encounter the challenges of increasing the load capacity while the environmental sustainability should be achieved. However, it has been realised that the environmental assessment of railway bridges has not been integrated into the decision-making process, the standard guideline and criterion is still missing in this field. Therefore, the implementation of life cycle assessment (LCA) method is introduced into railway bridges. This article provides a systematic bridge LCA model as a guideline to quantify the environmental burdens for the railway bridge structures. A comparison case study between two alternative designs of Banafjäl Bridge is further carried out through the whole life cycle, with the consideration of several key maintenance and end-of-life scenarios. Six impact categories are investigated by using the LCA CML 2001 method and the known life cycle inventory database. Results show that the fixed-slab bridge option has a better environmental performance than the ballasted design due to the ease of maintenances. The initial material manufacture stage is responsible for the largest environmental burden, while the impacts from the construction machinery and material transportations are ignorable. Sensitivity analysis illustrates the maintenance scenario planning and steel recycling have the significant influence on the final results other than the traffic disturbances.

Keywords: environment; global warming; life-cycle performance; infrastructure management; maintenance; rail track design

Introduction

The construction activities are deemed to be the largest contributor to global resource use and pollution emissions (Lorenz *et al.* 2008). Specifically for the railway bridge infrastructures, they represent an important role among the entire transportation and construction sector. However, railway bridges are not environmental friendly structures. During their long life span, large amount of material and energy flows are involved through their complex life scenarios. It has been realised that the current decision making of railway bridges is mainly oriented on the technique, safety and economic perspectives, that the environmental assessment is not integrated and considered. The environmental assessment for railway bridges may set a new design criterion; provide the sustainable concept for design optimisation and scenario planning.

Life cycle assessment (LCA) has proved to be an effective method for quantifying and assessing the environmental impacts of a product or service throughout its whole life cycle, from 'cradle to grave' (ISO14040 2006). Even though LCA as a decision supporting tool has been widely used in a variety of fields, its application for railway bridges is still rare. Very limited research and literatures can be found in this field. Due to the complexity of the railway bridge structures and life cycle scenarios, it is difficult to perform LCA without sufficient bridge knowledge. Several problems remain as obstacles preventing the application of LCA for railway bridges, such as lack of life cycle inventory (LCI) data, standard guidelines and criterion. The absence of a systematic LCA bridge model is another problem that requires the concentrated efforts.

In this article, a generalised LCA model is presented, aiming at systematically assessing the environmental burden of railway bridges throughout the whole life cycle. This 'Bridge LCA model' is further illustrated on the Banafjäl Bridge, as a case study for comparing two alternative designs: one with ballast track design and another with fixed-slab track design. The study is performed through the whole life cycle with the investigation of the critical structural components and the key life cycle scenarios in each design alternative. A sensitivity analysis is also carried out in terms of the steel recycling rate, the traffic disturbance and maintenance schedule plan.

Methodology and framework

Based on the investigation of current railway bridge systems in Sweden, a systematic Bridge LCA model is

*Corresponding author. Email: guangli.du@byv.kth.se

ISSN 1573-2479 print/ISSN 1744-8980 online

http://dx.doi.org/10.1080/15732479.2012.670250
http://www.tandfonline.com

developed, as shown in Figure 1. With multi-levels of detail, this model servings as a generalised framework to assess the environmental performance of the bridge system from a whole life cycle manner, either for the entire bridge or a part of structural components. The model takes account of the bridge structural elements including the railway track, superstructure and substructure; each of them is connected to a specific material type. The LCI data with embedded manufacturing process are further assigned to the

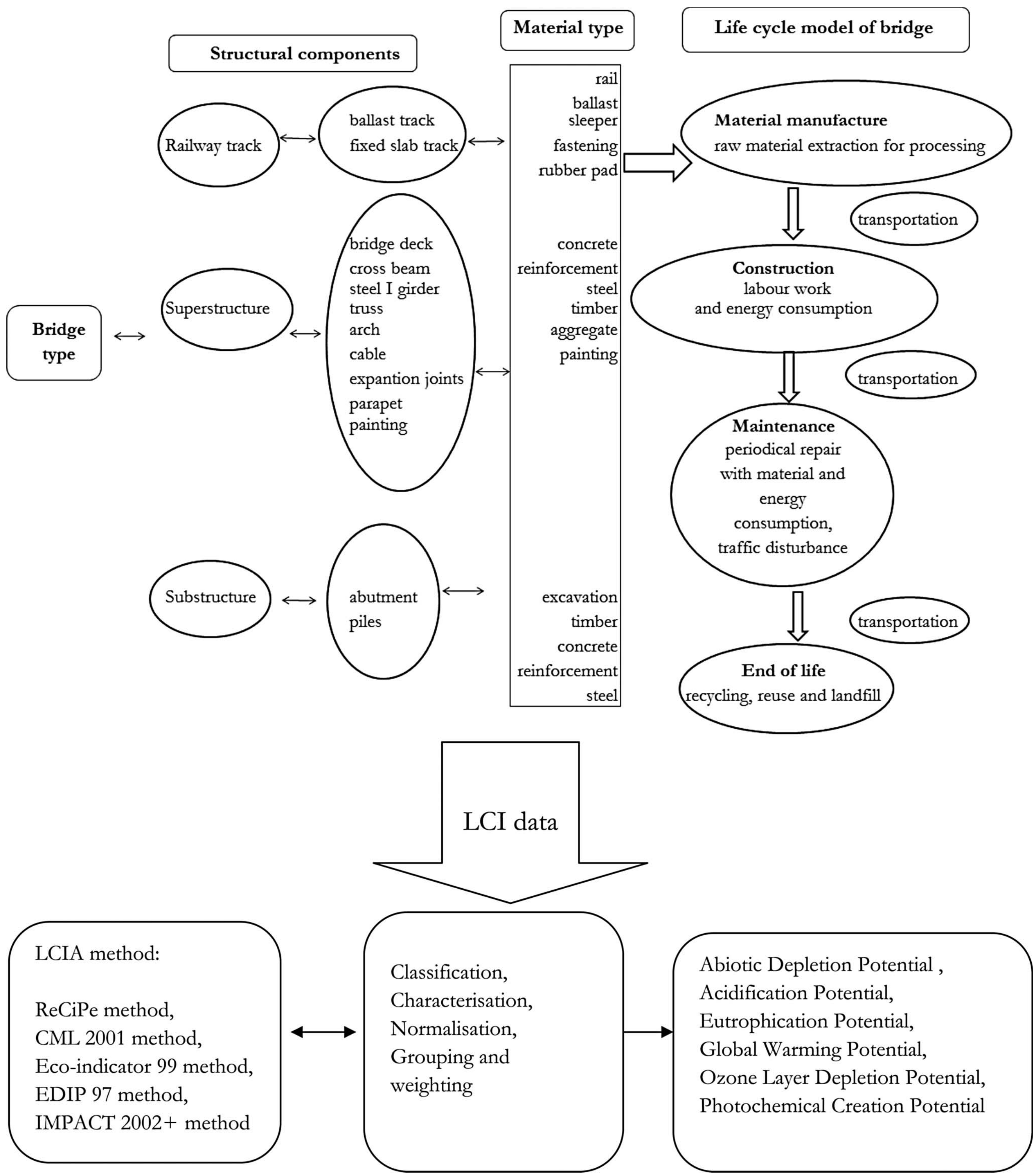


Figure 1. Bridge life cycle model.

selected material. This model is treated as the input to the life cycle impact assessment (LCIA). Currently, various LCIA methods are available, such as ReCiPe method, CML 2001 method, Eco-indicator 99 method, EDIP 97 method and IMPACT 2002+ method illustrated in Hischier *et al*. (2009). The final result may vary due to different LCIA methods applied. However, there are still no guidelines from the authority setting the criterion for the method selection. The recommendations of a broad set of life cycle stages are listed below:

Material manufacture phase

This takes accounts of the environmental burden due to the material manufacture, from the raw material mining until obtaining the final products at the factory gate. Through a bridge life cycle, large amount of construction material would be produced and result into the air, water and solid releases. The commercial LCI database provides the unit environmental profile for each material type, taking account of the raw material extraction, sub-material transportation, energy consumption and waste treatment. A large number of LCI database are developed by different institutes and companies. However, those databases still do not cover all of the materials' environmental profile. In the real case studies, the site-specific LCI data are always preferable than the commercial LCI databases.

Construction phase

This focuses on the environmental burden from the use of the construction equipments, such as the earthwork cranes, forklift trucks, the excavators on site and the related transportations. Currently, there are several methods widely used for the construction stage of bridges: (1) full span supporting method; (2) precast segmental method; (3) balanced cantilever form-traveller cast method and (4) incremental launching method (Guangzhou University 2009). Each of those construction approaches may lead to different energy efficiency in the construction machine, thus would further affect the environmental performance. If the data are available, the material and energy consumption due to the associated scaffoldings and supporting systems should be counted.

Maintenance and use phase

The railway bridges have a long life span which requires regular maintenance activities. Consequently, the machinery operation, related traffic disturbances and extra material consumption will result in extra environmental burdens. It has been realised that the well scheduled maintenance scenarios can efficiently prolong the service life and thus improve the environmental performances in a long-term. For example, Table 1 shows a series of maintenance activities for railway bridges recommended by Tirus *et al*. (Tirus, H., Andersson, A., and Prokopov, A., 21 December, 2010. Personal contact by email. Trafikverket, Sweden). It shows that a fixed-slab bridge has an easier maintenance schedule than the ballast bridge. However, the realistic maintenance intervals are largely influenced by the designed service life, train load, periodic inspection and budget plan. During the maintenance phase, the quantity of consumed material and energy are estimated from the realistic maintenance information. From which, high levels of uncertainty are introduced into the LCA modelling. A number of those activities require a traffic closure, it is important to evaluate the related environmental burdens.

End of life phase

This covers the environmental impact from several end-of-life (EOL) scenarios. The demolition wastes from the bridge are sorted into different treatment scenarios, including reuse or recycling, incineration and final landfills. Concrete, reinforcement and steel are the most commonly used material in bridges, within which steel is 100% recyclable and the scrap can be converted into the same (or higher or lower) quality steels (IISI 2005). In general, the material recycling in the EOL stage is expected to benefit the environment, in terms of reducing the original material consumption and the discharge of associated emissions. However, it has been criticised that recycled material could also generate more environmental burdens than using virgin one due to the high-energy consumption in the complex recycling process. This issue has been pointed in several literatures as Georgakellos (2006); Vieira and Horvath (2008) and Blengini (2009). The selection of EOL strategies is thus important for the final

Table 1. Maintenance activity during the whole life cycle (Tirus, H., Andersson, A., and Prokopov, A., 21 December 2010. Personal contact by email. Trafikverket, Sweden).

Structural element	Maintenance activities	Ballast track	Fixed-slab track
	Rail grinding	1 year	1 year
	Track direction	0.5 year	no repair
	Rail replacement	25 years	25 years
Railway track	Sleeper renewal	50 years	no repair
	Fastener renewal	25 years	25 years
	Rubber pad renewal	25 years	25 years
	Ballast renewal	20 years	no repair
Superstructure	Repainting	30 years	30 years

environmental performance of the bridge. For the LCA of bridges, the future EOL scenarios are mostly assumed based on the current technologies.

Case study of the Banafjäl Bridge

In order to compare the environmental performance of two design options of the Banafjäl Bridge, the bridge LCA model is implemented. The Banafjäl Bridge is a single track railway bridge, with a 42 m span, 7.7 m width located on the Bothnia line, Sweden. This bridge is originally designed with ballast track, as shown in Figure 2. However, due to the improved railway efficiency, Gillet (2010) did an alternative design with fixed-slab track option for the whole superstructure based on the static and dynamic test, as shown in Figure 3. The main body of the bridge consists of a reinforced concrete deck supported by two steel I-girder beams, as shown in Figure 4. The two design alternatives are differed from the railway track systems, bridge slab and the main steel I-girders. Table 2 shows the dimensions of the steel beams, including the web height and thickness $h_w \times t_w$, the up flange width and thickness $b_u \times t_u$, and the bottom flange width and thickness $b_l \times t_l$.

Scope of the study

The comparative LCA analysis is focused on the whole life cycle of two bridge design alternatives, from the material manufacture phase, through construction phase, use and maintenance phase, till the end of the life with a life span of 120 years. The study covers the railway track system, bridge slab and steel I-girder

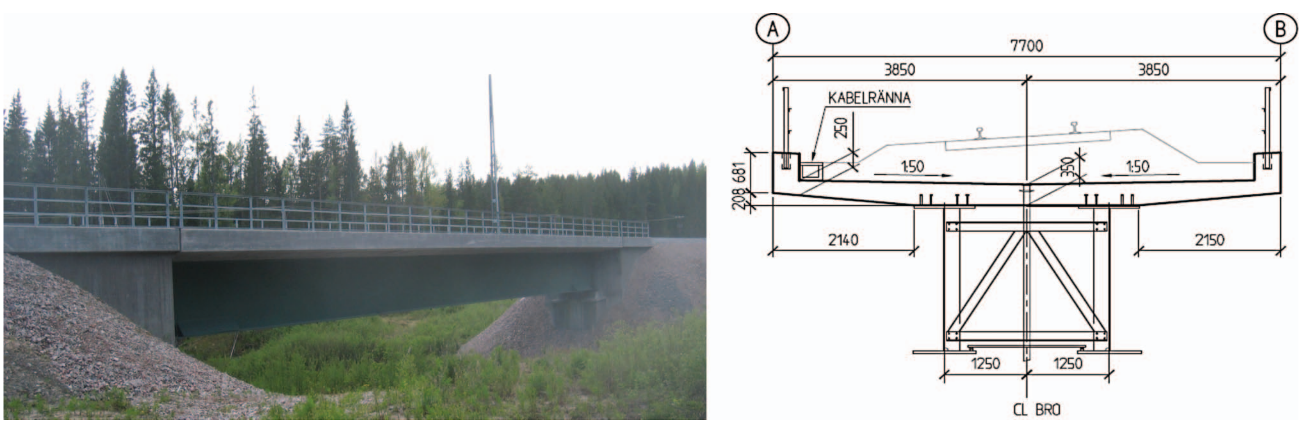


Figure 2. Ballast track alternative.

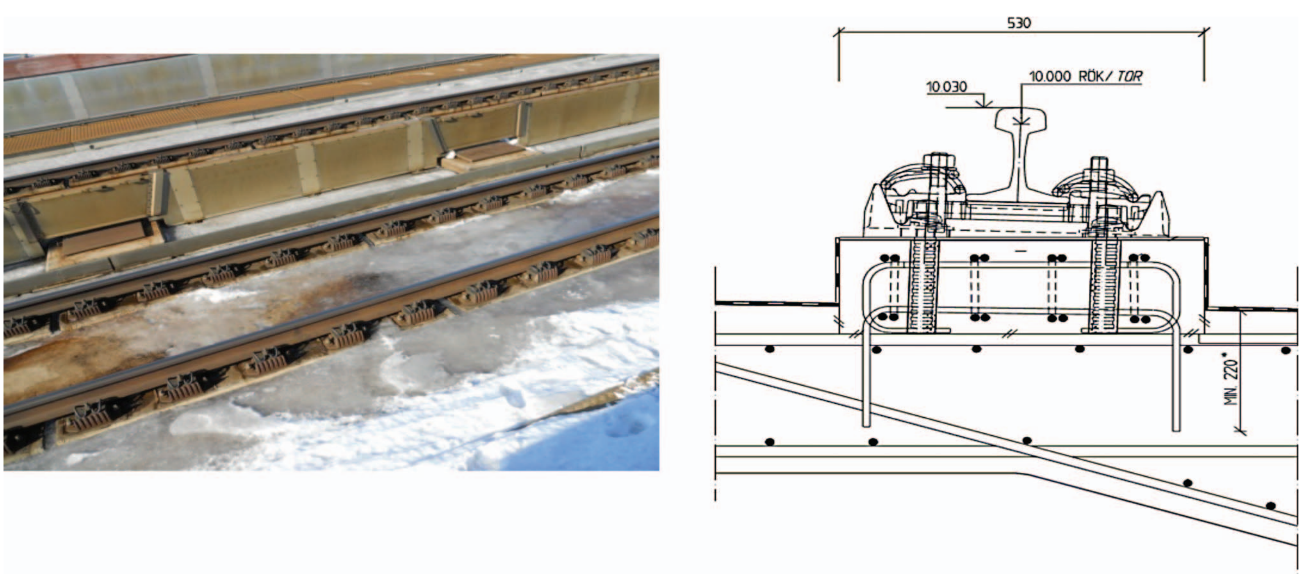


Figure 3. Fixed-slab track alternative.

beams. However, the bridge substructure, which assumes to be identical for both design options, is excluded from the study. The functional unit is chosen as 1 m unit length of the bridge system in the longitudinal direction, serving the same annual traffic volume with a life span of 120 years. The Banafjäl Bridge as part of the Bothnialine, its annual traffic volume is considered to be 343,800,000 pkm of passenger and 506,400,000 tkm of the freight transport up to 2020 (Bothniabanan 2010). Both of the life cycle inventory data and the material quantities are calculated on the functional unit basis in the further analysis.

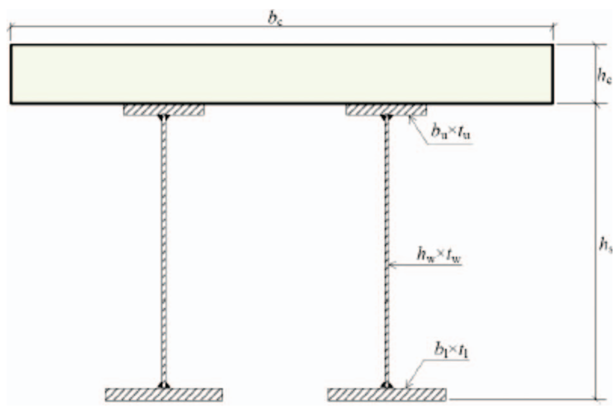


Figure 4. Steel I-girder of the Banafjäl Bridge.

Table 2. Steel section dimensions.

	t_u (mm)	b_u (mm)	h_w (mm)	t_w (mm)	t_l (mm)	b_l (mm)
Ballast design option	48	900	2397	17	55	950
Fixed-slab design option	46	900	2409	14	45	900

This bridge is originally designed with ballast track, as shown in Figure 2. However, due to the improved railway efficiency, Gillet (2010) did an alternative design with fixed-slab track option for the whole superstructure based on the static and dynamic test, as shown in Figure 3. The main body of the bridge consists of a reinforced concrete deck supported by two steel I-girder beams, as shown in Figure 4. The two design alternatives are differed from the railway track systems, bridge slab and the main steel I-girders.

Life cycle of the Banafjäl Bridge

The life cycle of the Banafjäl Bridge is analysed on the basis of the Bridge LCA model, which in general considers the four life stages, including: material manufacture stage, the construction stage, maintenance stage and the EOL. Table 3 shows the structural elements and processes considered in the case study scope. The material manufacture stage includes the entire raw resource and energy flows for the material processing. The related environmental burdens are obtained from the selected LCI database. The construction phase considers the diesel and fuel burned in the construction machine, while the transportation and labour work are omitted due to lack of information. The maintenance phase focused on the scheduled periodic renewal of the structural components as well as the goods transportation, see Table 1. Usually, if a small part of the structural components needs a replacement on site, the whole component will be replaced at the same time, thus the same material and energy flow are assumed as in the initial construction stage. The traffic disturbance due to the maintenance activities are considered separately in the sensitivity analysis. At the EOL stage, the bridge will be demolished and sorted for different waste treatments. The current steel recycling rate for the construction plate and beam is considered to be 88% (Fenton 2004). Based on those

Table 3. The life cycle of the Banafjäl Bridge with two design options.

Life cycle of the Banafjäl Bridge				
	Railway tracks	Bridge deck	Steel I-girder	
Material manufacture stage	Ballast, fastening clips, sleepers, rails, rubber pad	Concrete slab, reinforcement	Cross stringers, steel I-girder, painting	Transportation processes
Construction stage	Energy consumption in the construction machine			
Maintenance stage	Ballast, fastening clips, sleepers, rails, rubber pad	N/A	Painting	
End of life stage	Concrete crush, steel recycling, landfill			

considerations, several EOL scenarios are assumed, that the concrete is modelled by crushing into gravel and disposal for landfill, the steel is modelled by 88% recycling and 12% landfill. All of the material and energy inventories involved in those activities are obtained from LCI database.

Life cycle inventory of the Banafjäl Bridge

The LCI data take account of the material and energy flows as input data, and the associated waste releases as output in each material manufacture process. In this case study, the detailed material data for the two alternative design options are collected from four LCI databases: Ecoinvent version 2.1, ELCD version 2.0 (2006), world steel and U.S. LCI (NREL 2005). Table 4 shows the considered structural components with the corresponding LCI database. The material and energy consumption for the initial construction are mostly obtained from the realistic design drawings and recorded project information, which are described below.

Rail. The Swedish railway administration currently uses UIC60 profile rail track equipped with e-clips, with steel quality R260 and R350 (Nyström and Gunnarsson 2008). The mass quantity for the continuously welded UIC 60 single rail track is 120 kg/m, and the material type is modelled by 18/8 chromium steel from the ELCD version 2.0 database for both design alternatives.

Ballast. For the ballast design option, the ballast is modelled by the crushed stone material with a density of 20 kN/m^3. The ballast mass is weighted as 8.3 ton/m by 6.9 m $\times$ 0.6 m in the geometry of the rectangular shape.

Sleepers. The sleepers are designed by the reinforced concrete blocks for both track alternatives. According to the Rail Administration's requirements, each sleeper is weighted as 300 kg and separated by a spacing of 0.60 m (Nyström and Gunnarsson 2008). For the ballast track, the sleeper is dimensioned as 0.2m $\times$ 0.2m $\times$ 2.5m with the concrete quantity of 0.17 m^3/m and reinforcement of 10 kg/m. For the fixed-slab track system, the quantity of the concrete and reinforcement is 0.091 m^3/m and 14.8 kg/m, respectively.

Fastening clip. According to the Swedish railway administration, the fastening clip of both ballast and fixed-slab track is modelled on the Pandrol fastening clip system. Pandrol manufactures a range of rail fastenings with a typical dimension of 15 mm diameter; the total weight of each fastening clip combined with a toe insulator is 620 g (Hamilton, B., 2010. Personal contact by email, Rosenqvist Rail AB, Sweden). The fastening clip of the Banafjäl Bridge is calculated to be 4.13 kg/m.

Reinforced concrete slab. The reinforced concrete slab of the Banafjäl Bridge is identically designed

Table 4. Material summary for the two bridge design alternatives.

	Ballast track option	Fixed-track option	Service life	Type of material	Database
Superstructure					
Reinforcement	346 kg/m	346 kg/m	N/A	Reinforcing steel, at plant	Ecoinvent database v2.1 (2009)
Concrete slab	6280 kg/m	6280 kg/m	N/A	Concrete, sole plate and foundations, at plant	Ecoinvent database v2.1 (2009)
Steel section	2139 kg/m	1815 kg/m	N/A	Welded steel plates	World Steel Association[2]
Cross stringer	31 kg/m	31 kg/m	N/A	Hot rolled steel section	ELCD v2.0
Painting	13.74 m^2/m	13.55 m^2/m	30 years	Paint – top coat, per m^2	U.S. LCI database
Track system					
Rail	120 kg/m	120 kg/m	25 years	Steel, converter, chromium steel 18/8, at plant	Ecoinvent database v2.1 (2009)
Ballast	8.3 ton/m	–	20 years[1]	Crushed stone 16/32, open pit mining, production mix	ELCD v2.0
Rubber pad	4.2 kg/m	4.2 kg/m	25 years	Rubber, normal	Ecoinvent database v2.1 (2009)
Concrete of sleepers	0.17 m^3/m	0.091 m^3/m	50 years	Concrete, normal, at plant	Ecoinvent database v2.1 (2009)
Reinforcement of sleepers	10.16 kg/m	14.8 kg/m	50 years	Reinforcing steel, at plant	Ecoinvent database v2.1 (2009)
Fastening clip	4.13 kg/m	4.13 kg/m	25 years	Hot rolled stainless steel, grade 304 RER S	ELCD v2.0

Note: [1]Only ballast track system. No ballast and sleeper replacement for slab track system during maintenance stage.
[2]Broadbent, C., 2011. Personal contact by email with the World Steel Association (former IISI).

for both design options, with a curvature radius of 4000 m and the concrete slab thickness varies from 250 mm to 400 mm. The calculation of the quantity of concrete and reinforcement is based on realistic design drawings. The material quantity is calculated as 6280 kg/m for the concrete and 347 kg/m for the reinforcement, including longitudinal reinforcement, transversal reinforcement and stirrups.

Steel I girder. Table 2 shows the dimensions of the steel I-beam for both ballast track and fixed-slab track alternatives as designed by Gillet (2010). The steel section is calculated as 2139 kg/m for the ballast option and 1815 kg/m for the fixed-slab option. Due to the lack of good data, the model is performed by the LCI data of steel plates obtained from the world steel, from which the environmental burden of welding process is omitted.

Crossing stringer. This is calculated as 31 km/m for both alternatives, by the LCI data of hot rolled steel section provided from ELCD version 2.0.

Replacement of the rubber pads. The regular replacement of the rubber pads is carried out together with the rail maintenance. The material quantity of the rubber under the rail foot is 4.2 kg/m for both design options and modelled by the data from Ecoinvent database version 2.1.

Painting. The painting amount is considered as the surface area of the steel I-girder, which is 13.74 m^2/m for the ballast option and 13.55 m^2/m for the fixed-slab option. The material is modelled on the values of paint from the US LCI database (NREL 2005).

Transportation process. The material transportation is modelled by the truck lorry 3.5–20 t full fleet. The distance is estimated by the realistic distance between the site and the potential suppliers. It is assumed that all the concrete is transported from the factory in nearby city Övik within the distance of 30 km; the steel, reinforcement and ballast are purchased from the city of Sundsvall within 100 km.

Energy consumption. Both diesel and gasoline consumption during the construction stage are considered in the model. Due to the unavailability of data, the assumption of the quantity consumed is calculated on the basis of Lee *et al*. (2008). Lee *et al*. (2008) concluded that a 30 km ballast track consumes 376 L diesel and 25 L gasoline during the construction phase, while for the same length of fixed-slab track the values are 33.9 L and 10 L, respectively. Based on the similarity of the structural type, the diesel and gasoline consumption for the Banafjal Bridge alternative designs have been calculated equivalent based on the functional unit, that diesel consumption is 0.0125 L/m and 0.0011 L/m for each design alternative, and the gasoline consumption is 0.0008 L/m and 0.0003 L/m, respectively.

Results

In this case study, the CML 2001 assessment method is applied with the software tool SimaPro version 7.2 (2010). The normalisation factors from Western Europe '95 are shown in Table 5. Six impact categories oriented at a 'mid-point' level of human health and ecosystem are investigated, including: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP100), Ozone Layer Depletion Potential (ODP) and Photochemical Oxidation Potential (POCP).

Figure 5 shows the normalised results of environmental impact allocation due to each structural component through the life cycle except the EOL. It has been found the element of steel I-girder beam, reinforced concrete slab and the UIC60 rail are the main contributors in both design options, which totally account for up to 86% in GWP, 83% in ADP, 86% in AP and 82% in EP. The reason is due to the large consumptions of steel and the high embodied environmental burdens of the steel manufacturing. Moreover, compare to the ballasted option, the fixed-slab option gives a better environmental performance in each impact category. Not only because the fixed-slab design consumes less initial material, but also has fewer maintenance scenarios, that the replacement of sleepers, ballast and related transportations are all excluded from the regular maintenance.

Figure 6(1), (2), (3) and (4) shows the comparison of normalised environmental impact between two design options through the life cycle. In the first three stages, the fixed-slab bridge reveals a preferable environmental performance among all impact categories. The overall impact for GWP and AP is

Table 5. Normalisation factors.

Impact category	Unit	Normalisation factor
Abiotic depletion	kg Sb eq/yr	1.71E + 09
Acidification	kg SO_2 eq/yr	6.71E + 08
Eutrophication	kg PO_4 eq/yr	5.03E + 08
Global warming (GWP100)	kg CO_2 eq/yr	2.53E + 11
Ozone layer depletion	kg CFC-11 eq/yr	9.80E + 05
Photochemical oxidation	kg C_2H_4 eq/yr	1.82E + 08

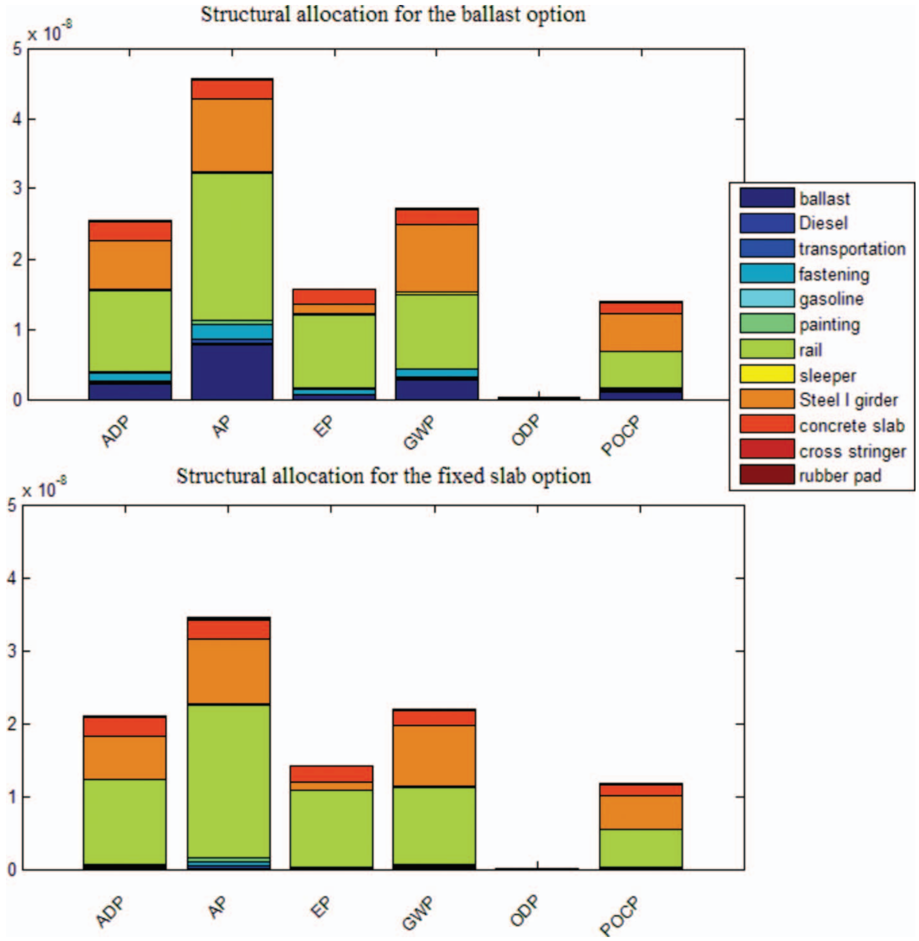


Figure 5. Environmental impact of structural allocation for the two design options.

significant while for ODP is negligible. In Figure 6(4), the negative sign denotes the potential environmental benefits due to the steel recycling, which largely overwhelms the impact from concrete landfill. That 88% steel is recycled and all the concrete are crushed for landfill. Frischknecht (2010) addressed two different approaches that currently applied in LCA recycling practice: the cut-off approach and the avoided burden approach. The avoided burden approach is implemented in this study for the steel recycling process, that 88% environmental burden is avoided from the production of original steel. Figure 6(5), shows the total environmental impact throughout the whole life cycle. It is noticed that the fixed-slab bridge is a preferable option, with the dominant impact from the category of AP and GWP. The environmental advantages are mainly due to the less material consumption and the ease maintenances.

Sensitivity analysis

The bridge structure is a complex system that consists of numerous structural components and various scenarios through its long life span. A high level of uncertainties is thus inevitably involved in the LCA model. The uncertainties may distinguished from various sources, including defined scope, applied LCA method, calculation of input data, assumptions of the future scenarios, differences between applied LCI data and the realistic local data. It is therefore necessary to perform a sensitivity analysis to identify how each parameter affects the overall result. This section is aimed at assessing the sensitivity from the parameters of the maintenance activity plan, steel recycling rate, traffic disturbances during the maintenance phase.

Maintenance scenarios

As shown in the final result, the maintenance activities take account of a large proportion in the environmental burdens, especially the steel material related scenarios, such as rail and steel section. In order to identify how important the schedule of maintenance activities can affect the final result, a sensitivity analysis is performed on the rail replacement. By decreasing the replacement interval of rails from every 25 years to

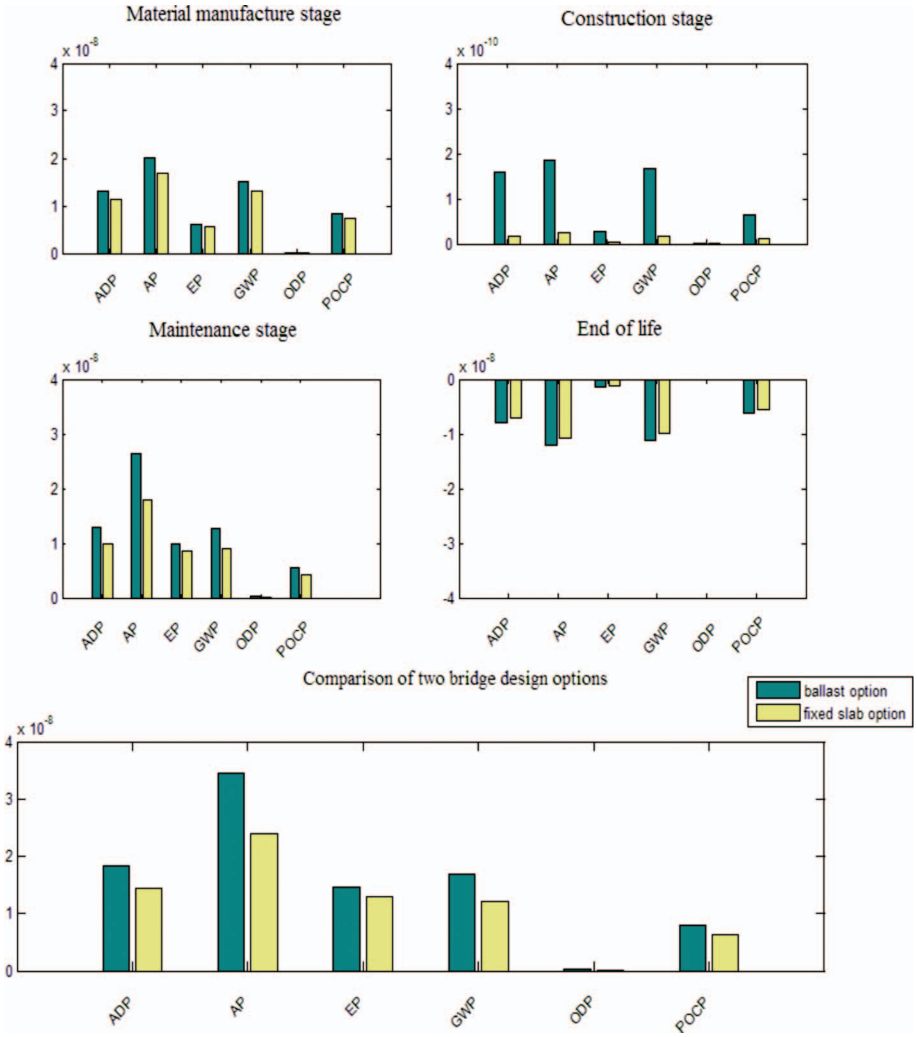


Figure 6. Environmental comparisons between the two bridge alternatives through the whole life cycle.

every 20 years, the environmental impact can vary up to 17% among all the categories, see Table 6. It has been found that the fixed-slab option obtains larger effect than the ballasted option.

End-of-life recycling scenarios

In order to identify how each environmental category is affected by the variation from the steel recycling rate, the sensitivity analysis is performed for the fixed-slab option by changing the steel recycling rate from 0%, 20%, 70%, 88% to 95%. Figure 7 illustrates the deviation of each environmental category against the normalised variation range of the steel recycling rate. The result indicates that the steel recycling rate has a significant influence for the category of POCP and GWP. It the fact that the recycling rate is a key parameter to consider, especially if the target category is oriented for the category of GWP.

Table 6. Characterised environmental impact variation due to rail replacement schedule.

Impact category	Abbreviation	Ballast option + Δ %	Fixed-slab option + Δ %
Abiotic depletion	ADP	13%	16%
Acidification	AP	12%	17%
Eutrophication	EP	14%	16%
Global warming	GWP100	13%	17%
Ozone layer depletion	ODP	7%	13%
Photochemical oxidation	POCP	13%	16%

Traffic disturbances

The Banafjäl Bridge is a single track railway bridge, thus the closure of train freight traffic is required during the maintenance activities. In this section, the sensitivity analysis is performed by considering the

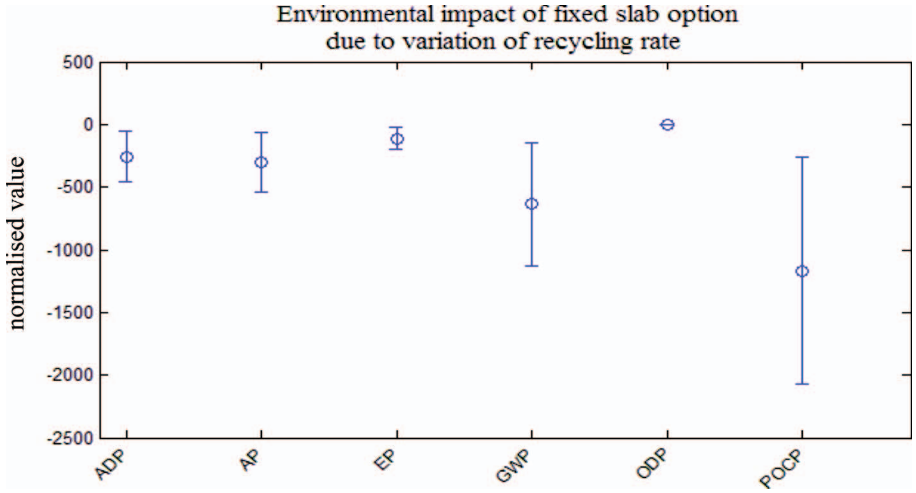


Figure 7. Environmental impacts of fixed-slab option due to variation of the recycling rate.

traffic disturbances during the maintenance scenarios, which is modelled by: the passenger traffic shift from the train to the car, and the train freight traffic shift from the train to the truck. Both of the LCI data from Ecoinvent database including the petrol passenger car and the freight truck lorry ($>$16t) are implemented in the model, those vehicle types reflect the general European condition. According to the Bothniabanan (2010) EPD report clarification, the annual passenger transport is considered to be 343,800,000 pkm and 506,400,000 tkm for the train freight transport along the 190 km Bothnia Line up to 2020. Based on the functional unit defined of '1 m bridge superstructure in 120 years service life' and the estimated maintenance scenarios in Table 1 (Tirus, H., Andersson, A., and Prokopov, A., 21 Dec., 2010. Personal contact by email. Trafikverket, Sweden), the traffic disturbance due to maintenance activities through the whole life cycle is calculated as equivalent to two days traffic closure for the fixed-slab track and seven days for the ballast track. The environmental effect due to the consideration of traffic disturbances during the maintenance stage is present in Table 7. The results show that the environmental impact due to traffic disturbance is ignorable, with the maximum effect varying by up to 0.83%.

Table 7. Environmental impact variation due to traffic disturbance.

Impact category	Abbreviation	Ballast option + Δ %	Fixed-slab option + Δ %
Abiotic depletion	ADP	0.43%	0.16%
Acidification	AP	0.31%	0.13%
Eutrophication	EP	0.29%	0.09%
Global warming	GWP100	0.42%	0.17%
Ozone layer depletion	ODP	0.83%	0.61%
Photochemical oxidation	POCP	0.28%	0.10%

Discussion and conclusions

The great amount of environmental burdens from the construction sector has attracted increased concerns worldwide. However, the railway bridges, as an important part in the construction sector, their environmental impact are not yet considered in the decision-making process. Currently, LCA as a systematic method has been used in a various areas, but very rarely applied for railway bridge structures. Lack of good data, guidelines, systematic model and criterion are the obstacles hindering the LCA implementation in this field. This article presented a Bridge LCA model for analysing the environmental impact of railway bridge structures. The model was further illustrated in a comparative case study between two railway bridge design options, with the LCA CML 2001 mid-point method and several LCI database. The analysis was performed through the whole life cycle of the bridge from the material extraction to the end of life. The environmental impact was evaluated based on the key maintenance and EOL scenarios, with the contribution from each structural element. In addition, due to the uncertainties involved in the study, a sensitivity analysis was carried out for testing the significance of maintenance planning, steel recycling rates and traffic disturbances. Six impact categories were investigated, including: Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP100), Ozone Layer Depletion Potential (ODP) and Photochemical Oxidation Potential (POCP). The following conclusions are made based on the study:

(1) The defined study scope, a change in the life-cycle scenarios, and the applied LCA method can greatly influence the final environmental results. Without performing LCA analysis, it is hard to draw a generalised conclusion for a certain bridge type. For instance, a contrary result was obtained in this article when comparing with the study from Lee *et al.* (2008). Due to the differently defined scope, Lee *et al.* (2008) found that the ballast track achieved a better environmental performance result. Another example is the traffic disturbance accounts for an ignorable effect in this study whilst it caused a significant impact in the arch bridge LCA study by Steele (2002). The main reason for those contrary results was the difference in the predefined life cycle scenarios, different study scope of the structures, certain structural type and the LCI databases applied. Moreover, various LCIA methods are developed for the LCA study. The final result may vary due to different LCIA methods chose. However, there are no guidelines from the authority setting the criterion for the method selection.

(2) The structural type affects the life cycle scenarios, thus further influencing the final environmental impact. Due to the ease maintenance strategy and the less material consumption, the fixed-slab option performs better environmental performance than the ballast design. For the bridge whole life cycle, the initial material consumption stage contributes to the largest environmental burden, while the impacts of the construction machinery and material transportation are ignorable. The use of the steel products, i.e. the I-girder beam, the rail tracks and reinforcement, was found to be the main environmental contributors of the bridge structure, which account for up to 86% of the final impact. For the EOL scenarios, the environmental benefits are considerable when comparing with using the virgin steel products. Without considering steel recycling, the steel consumption in the railway bridge accounts for up to 75% and 87% GWP for the ballast and fixed-slab options, respectively, which indirectly indicates that steel recycling, is an effective way to reduce the environmental impact.

(3) The bridge structure is a complex system with great uncertainties in the LCA model, thus a sensitivity analysis is necessary for identifying the effects of changing the key parameters. By performing a sensitivity analysis in terms of the maintenance plan, recycling rate and traffic disturbances, no significant effects were found from the traffic disturbance, however, the change of the replacement interval of rail lead to differences of up to 17%, and the steel recycling is also identified as an important method to reduce the environmental impact.

(4) The availability of the data and project information were shown to be the major problem in the bridge LCA study. For example, due to lack of information, the energy consumption of the construction machinery was obtained from another similar project. Most of the structural components in the study are modelled by the average LCI database instead of the realistic site data. The assessment of steel I girder beam is performed by the LCI data of steel plates obtained from the world steel, from which the environmental burden of welding process is omitted due to lack of good LCI data. Therefore, in order to obtain a more reliable result, it is important to establish a detailed LCI database that covers all the construction material and processes.

References

Blengini, G.A., 2009. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. *Journal of Building and Environment*, 44(2), 319–330.

Bothniabanan, A.B., 2010. Environmental Product Declaration for freight transport on the Bothnia Line. [online] Reg. no. S-P-00195, UN CPC 6512, Sweden. Available from: http://www.botniabanan.se/vitbokmiljo/dokument/5%202%209%20EPD%20for%20freight%20transport%20on%20the%20Bothnia%20Line.pdf [Accessed 27 April 2011].

Ecoinvent database v2.1, 2009. Swiss Centre for Life Cycle Inventories, EMPA St. Gallen Lerchenfeldstrasse 5 CH-9014. St. Gallen, Switzerland.

European Reference Life Cycle Data System (ELCD) Version 2.0, 2006. European platform on life cycle assessment, European Commission – DG Joint Research Centre, Institute for Environment and Sustainability.

Fenton, M.D., 2004. Iron and Steel Recycling in the United States in 1998, U.S. Geological Survey Circular 1196–G, Flow studies for recycling metal commodities in the United States, U.S. Department of the Interior.

Frischknecht, R., 2010. LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. *The International Journal of Life Cycle Assessment*, 15(7), 666–671.

Georgakellos, D.A., 2006. The use of the LCA polygon framework in waste management. *Management of Environmental Quality: An International Journal*, 17(4), 490–507.

Gillet, G., 2010. *Simply supported composite railway bridge: a comparison between ballasted and ballastless alternatives*. Master Thesis, Division of Structural Engineering and Bridges, KTH Royal Institute of Technology, Stockholm, Sweden.

Guangzhou University, 2009. *Overview of the World Bridge, the latest construction methods of concrete bridge, the latest technology innovation of bridge engineering*, Chapter 3. [online] China, Department of Civil Engineering, Guangzhou University. Available from: http://www.gzhubridge.com/news_dt.asp?id=743&class_code=00090004 [Accessed 27 April 2011].

Hischier, R., *et al*., 2009. *Implementation of life cycle impact assessment methods*. Ecoinvent report No. 3, v2.1. Dübendorf, CH: Swiss Centre for Life Cycle Inventories.

International Iron and Steel Institute (IISI), 2005. Steel: the foundation of a sustainable future, sustainability report of the World Steel Industry 2005. ISSN 1782-2025, 1–51. Brussels, Belgium.

ISO 14040, 2006. *Environmental management – life-cycle assessment – principles and framework*. Geneva: International Organization for Standardization.

Lee, C.K., Lee, J.Y., and Kim, Y.K., 2008. Comparison of environmental loads with rail track systems using simplified life cycle assessment (LCA). *WIT Transactions on the Built Environment*, 101, 367–372.

Lorenz, D., *et al*., 2008. *Sustainable property investment & management: key issues & major challenges*. RICS EU Public Affairs. [online] Brussels, Belgium. Available from: www.joinricsineurope.eu/uploads/files/Sustainable%20Property%20Investment%20and%20management%20RICS%20sept%2008.pdf [Accessed 27 April 2011].

National Renewable Energy Laboratory (NREL), 2005. U.S. life-cycle inventory database. Golden, Colorado.

Nyström, P. and Gunnarsson, J., 2008. State of the art report – Spårkonstruktioner för höga hastigheter, Huvudprojekt Järnvägssystem för 250 km/h och 320 km/h, Delprojekt: Spårkonstruktioner för ballasterade och ballastfria spår del 1. RCON and Banverket, Sweden. (In Swedish).

SimaPro 7.2, 2010. Netherlands: LCA Software PRé Consultants.

Steele, K., *et al*., 2002. Environmental impact of brick arch bridge management. *Proceedings of the ICE – Structures and Buildings*, 156(3), 273–281.

Vieira, P.S. and Horvath, A., 2008. Assessing the end-of-life impacts of buildings. *Environmental Science Technology*, 42(13), 4663–4669.