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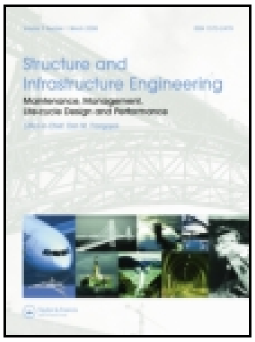
Published in:
Structure & Infrastructure Engineering

DOI (link to publication from Publisher):
10.1080/15732479.2012.749289

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Du, G., & Karoumi, R. (2014). Literature review of life cycle assessment for railway bridges: critical issues and framework. *Structure & Infrastructure Engineering*, *10*(3), 277-294. https://doi.org/10.1080/15732479.2012.749289



Structure and Infrastructure Engineering

Maintenance, Management, Life-Cycle Design and Performance

ISSN: 1573-2479 (Print) 1744-8980 (Online) Journal homepage: http://www.tandfonline.com/loi/nsie20

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To cite this article: Guangli Du & Raid Karoumi (2014) Life cycle assessment framework for railway bridges: literature survey and critical issues, Structure and Infrastructure Engineering, 10:3, 277-294, DOI: 10.1080/15732479.2012.749289

To link to this article: http://dx.doi.org/10.1080/15732479.2012.749289

Published online: 14 Dec 2012.

Structure and Infrastructure Engineering, 2014
Vol. 10, No. 3, 277–294, http://dx.doi.org/10.1080/15732479.2012.749289

Life cycle assessment framework for railway bridges: literature survey and critical issues

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(*Received 4 April 2012; final version received 27 July 2012; accepted 31 July 2012; published online 14 December 2012*)

Currently, the whole world is confronted with great challenges related to environmental issues. As a fundamental infrastructure in transport networks, railway bridges are responsible for numerous material and energy consumption through their life cycle, which in turn leads to significant environmental burdens. However, present management of railway bridge infrastructures is mainly focused on the technical and financial aspects, whereas the environmental assessment is rarely integrated. Life cycle assessment (LCA) is deemed as a systematic method for also assessing the environmental impact of products and systems, but its application in railway bridge infrastructures is rare. Very limited literature and research studies are available in this area. In order to incorporate the implementation of LCA into railway bridges and set new design criteria, this article performs an elaborate literature survey and presents current developments regarding the LCA implementation for railway bridges. Several critical issues are discussed and highlighted in detail. The discussion is focused on the methodology, practical operational issues and data collections. Finally, a systematic LCA framework for quantifying environmental impacts for railway bridges is introduced and interpreted as a potential guideline.

Keywords: life cycle assessment; railway bridges; environmental impact; sustainable construction

1. Introduction

The environmental burden due to the transportation infrastructures has attracted significant global concerns in the past years. For instance, Grossrieder (2011) found that the infrastructures in the Oslo-Trondheim high-speed line are responsible for 88% of greenhouse gases, in contrast to 12% by the train operation and rolling stock. Moreover, UIC (2009) pointed that, in comparison with the train operation and rolling stock, the infrastructures in the European Railway Network can account for 9% to 85% CO_2 equivalent emissions, which the ranging percentage is largely related to the condition of country topography, electricity mix condition, percentage of bridges/tunnels and the train efficiency. In addition, the European white paper 2011 set an ambitious strategic goal to shift 50% of all medium-distance transport from roads to rail or to waterborne transport by 2050, which will simultaneously require the increase of railway networks (Europa Press Releases IP/11/372). As the fundamental structures in a rail transportation network, bridges have considerable contributions to the resource depletion and pollution emissions through their long lifespan. Up to 2012, the Swedish authority owns 3842 railway bridges and 145 tunnels and over 13,642 km railway tracks (Erbén L., 28 May 2012. Personal contact by email. Trafikverket, Sweden). However, most of their current environmental assessments are only done for passenger transportation, ignoring the impact from the construction of the related infrastructures.

Life cycle assessment (LCA) is regarded as a comprehensive framework compiled with the ISO standards, for assessing the environmental impacts of products or services throughout its whole life cycle (ISO14040, 2006). Served as a systematic tool, LCA has been widely applied in the industrial fields of production, agriculture and building service, but very rarely for the railway bridge infrastructures. The railway bridge management is still mainly focused on the technical, safety and economic perspectives without considering the environmental impact. It has been noticed that the LCA for railway bridges is still new, lacking of internationally agreed guidelines and criteria. There are some limited literature and research studies available for the LCA of roadway bridges, but very few for railway bridges. The incorporation of LCA in railway bridge infrastructures is a challenging issue, involving a variety complex components and processes through a long lifespan.

Due to these considerations, this article is intended to present a detailed state-of-the-art survey for the current LCA development for bridges, available analysis tools and related life cycle inventory (LCI) databases. Critical comments are specified for either the LCA limitations or the appeared operational issues. Based on these,

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a theoretical LCA framework for railway bridges is to be introduced, addressing a set of key issues. The goal is to better understand the LCA implementation for railway bridges, thus to promote LCA as a decision-supporting tool in the bridge management and to set new design criteria towards environmental design.

2. General principles of LCA

LCA is a standardised and systematic method that evaluates the potential environmental impacts of a product or a service throughout its whole life cycle, from raw material acquisition, manufacture, use and maintenance till the end of the life (EOL) of its function. The potential environmental burden covers the resource depletion, human health and ecological health (ISO14040, 2006). Although today's LCA has been involved in a wide range of industrial sectors, with various tools and methodologies formulated, its application is historically new as it was initiated in the 1970s. The international standards ISO 14040 and ISO 14044 are available for LCA; however, it has been realised that they were only developed for general guidance purposes rather than for practical specifications (Fava, 2011), thus, lack detailed instructions or illustrations regarding how to perform the LCA practically. This section mainly outlines the necessary phases involved in LCA and the related most critical issues.

2.1. *Goal and scope of definition phase*

The LCA framework initiates with goal and scope definition, for the purpose of selecting the proper methodology and relevant categories. The determination of the scope of the study, the purpose and assumptions should be addressed clearly, as well as the inclusion of lifespan phases, relevant future scenarios and product components. This step is the most important and mandatory part for every LCA study, since the statement will affect the course of the entire study and will also guarantee clear external communications following completion of the study (Guinée, 2002).

2.2. *Life cycle inventory phase*

The LCI takes account of the inputs and outputs related to the product, which requires numerous data both regionally and globally. The process considers the energy and raw material as input to the model, and the environmental releases of gas, liquid and solid discharges as output. The inventory data of the energy, transportation, material consumption and waste treatment can be collected from various sources of factory, government, commercial databases and scientific journals.

2.3. *Life cycle impact assessment phase*

Life cycle impact assessment (LCIA) is the third stage in LCA, which converts the inventory emission data into the damage indicators or into the intuitive aggregated potential environmental impacts. Baumann and Tillman (2001) addressed that LCIA is the major and most time-consuming process in the LCA analysis. LCIA consists of several sub-processes of classification and characterisation, and optional sub-processes of normalisation, grouping and weighting (ISO 14044, 2006).

2.3.1. *Classification*

In this step, the relevant impact categories are selected on the basis of the goal and scope of the study. The classification process categorises the LCI emission substances into those impact categories, based on the chemical–mechanical contribution of those substances.

2.3.2. *Characterisation*

The emission substances are assigned and aggregated into the relevant environmental category, with the application of characterisation factors that are measured in the same scale. The characterisation stage converts the LCI emissions result into the environmental category.

2.3.3. *Normalisation*

This optional step compares the characterised results with the regional reference value on the basis of each category, which allows identifying the impact significance of the category under study within the total impact in that region.

2.3.4. *Grouping and weighting*

These are two optional steps for easing the interpretation procedure. The step of grouping sorts and ranks the characterisation results into several sets, such as global/regional/local or high/medium/low, whereas weighting evaluates the relative importance of each impact category among all the others based on the political and society evaluation (Baumann & Tillman, 2001).

2.4. *Interpretation*

Interpretation refines the numerous LCA results into specific explanation with meaningful conclusions. ISO 14040 defines that in the interpretation phase of LCA, the findings of either the inventory analysis or the impact assessment, or both, are combined in a consistent manner with the defined goal and scope in order to reach conclusions and recommendations. During this stage, issues related to potential limitations, drawbacks and uncertainties should be clearly revealed.

3. Discussion of critical issues in LCA

3.1. Lack of proper data

According to Curran, Notten, Chayer and Cicas (2006), Table 1 provides an overview summary of LCI database that emphasises on the construction field, with the condition adjusted to various regions. So far, there are numerous commercial LCI databases across diverse industry sectors, covering a wide range of manufacturing technologies. The quality of LCI data is usually dependent on the involved processing activities and regional technology. However, the lack of proper LCI data is still a key obstacle for performing LCA. Mainly because there are numerous types of materials and processes involved in an LCA study; i.e. the manufacture technologies of each material differ from one region to another, even the same material may have varying environmental profiles due to different circumstances. The LCI data of each material largely rely on the varying technology, regional conditions and scope of the information. Thus, a biased result may be obtained when applying different LCI databases. Consequently, maintaining LCI data transparent and performing uncertainty analysis are vital to ensure the reliability of the results. Although the LCA practitioner could obtain the LCI data from commercial LCI database, published literature, manufacturer documents and site interviews, realistic LCI data provided by the manufacturer are always preferable, but often unavailable. None of the current LCI database can explicitly cover all of the material types with specified processing procedures. Moreover, the real production process of the selected material often is ambiguous for LCA practitioners. The development of a consistent and international-level-based database remains a goal, which needs the cooperation among practitioners, public authorities and companies.

3.2. Various LCIA methodologies

With the development of LCA, various LCIA methods have been presented and are now available for the inventory results presentation, consistent with the ISO standards. Table 2 presents the example of impact indicators considered in different LCIA methodologies based on Barbara, Kellenberger, Alcorm, and Garrett (2009). Although those LCIA methods are developed following the same principles and framework derived from ISO standards, due to the complexity of the environmental mechanisms and regional regulations, they still differ from the considered category groups, orientation levels (midpoint or endpoint), included elementary LCI emissions, analysis factors and the covered LCIA steps (normalisation, grouping and weighting). Obviously, the variation of any of those mentioned parameters can largely affect the final results.

It has been mentioned in several studies in the literature that various LCIA methods may lead to different results. For instance, Althaus et al. (2010) investigated several commonly used LCIA methodologies (such as the CML 2007 method, Eco-indicator 99' method, EDIP method, IMPACT 2002 + method, TRACI method and ReCiPe method) and stressed that each of them emphasises particularly on either the midpoint level or the endpoint level. There is a wide variety of the key impact categories and analysis factors in each of these LCIA methodologies; thus, LCA results largely depend on the selected method. A certain impact category may be significant in one LCIA method, whereas it can be negligible in another method; for example, the category of abiotic depletion potential (ADP) is included in the CML method but excluded in the TRACI method; category of carcinogens and non-carcinogens is included in the method of Impact 2002 + and TRACI, but treated distinctly as human toxicity in the method of CML 2007. For this reason, Landis and Theis (2008), by comparing different LCIA methods regarding biofuels, pointed out that there is not exactly 'one right LCIA method'. In general, it is preferable to use the newest LCIA method in practice. For instance, the ReCiPe method, which was updated in 2012, splits the results into 18 single indicators at the midpoint level and 3 aggregated indicators at the endpoint level. Besides, the individual study goal and scope is another influential consideration.

The assessment process and LCI data collecting step through LCA are also complex and time –consuming; therefore, efficient LCA software tools have been developed, with a wide range of embedded LCI database sources and LCIA methodologies. Such tools are intended to ease the LCA analysis procedure, whereas as mentioned above, the final results still largely rely on the selected methods and databases. Table 3 gives an overview of LCA software that is oriented only in construction of technical works. The list has been based on the work of Jönbrink, Wolf-Wats, Erison, Olsson, and Wallén (2000). Most software tools in the list aim at analysing the building sectors, except the computational platforms of Simplified LCA (Thiebault, 2010) and ETSI BridgeLCA (Hammervold, Reenaas, & Brattebø, 2009) that are recently developed in the Nordic countries, which are specialised for bridge analysis. Due to the complexity of the railway bridge structures and long lifespan, none of the current LCA tools can provide complete inventory data that can cover all material and life-functioning scenarios. Most tools require further LCI data collection and a sufficient knowledge of bridge conditions for realistic scenario modelling.

Table 1. LCI databases.

Database name	Managed by	Description
LCI of Portland cement concrete	Portland Cement Association PCA R&D Serial No. 3011 http://assets.ctlgroup.com/aea962c9-279b-4cf2-9dac-9706094e408e.PDF	The LCI of ready mixed concrete, concrete masonry and precast concrete
World steel LCI	Former IISI http://www.worldsteel.org	A global LCI database specified for the steel products
European reference life cycle database (ELCD)	European Commission http://lct.jrc.ec.europa.eu	LCI database of key materials, energy consumption, transportation and waste management for the average European condition
US database	US National Renewable Energy Laboratory (NREL) http://www.nrel.gov/lci/	Various material, energy and assembly in the US condition, which is compatible with international databases
SPINE@CPM database	Chalmers University of Technology, Sweden http://www.cpm.chalmers.se	The Swedish national LCI database of detailed material, transportation, energy and waste management
Ecoinvent v2.2	The Swiss Centre for Life Cycle Inventories http://www.ecoinvent.ch	LCI database covers energy, transportation, material manufacturing of most industry fields oriented for the average European condition
IdeMat	Delft University of Technology http://www.idemat.nl/index.htm	Series of common material as glass, metals, polymers, woods, etc.
Stripple (2001)	IVL Svenska Miljöinstitutet AB http://www.ivl.se/download/18.7df4c4e812d2da6a416800071481/B1210E.pdf	Simplified LCI database report for the road construction material for the Swedish condition
Zygomalas et al. (2012)	http://dx.doi.org/10.1080/15732479.2010.519711	A newly developed LCI database for commonly used structural steel components

3.3. *Arbitrary results due to normalisation and weighting*

Normalisation and weighting are optional steps within the LCIA process. Normalisation compares the actual characterisation results with the reference results, whereas weighting relies on political, monetary, ethical and cultural viewpoints. The normalisation factors may have varying value in different LCIA methods as shown in Table 4. For example, the category of acidification differs by 52% from EDIP 97 to the global region (Stranddorf, Hoffmann, & Schmidt, 2003), whereas the category of global warming potential (GWP) was updated from 8.7E + 03 kg CO_2 eq/person/year in EDIP97 to 7.7E + 03 in EDIP2003 (Laurent, Olsen, & Hauschild, 2011). Since there is no societal consensus on these fundamental values, there is no reason to expect consensus either on the weighting factors or on the weighting method, or even on the choice of using a weighting method at all (Finnveden, 1999). Moreover, the International Reference Life Cycle Data System Handbook (European Commission, 2010) pointed that if the study is intended to support a comparative assertion to be disclosed to the public, no form of numerical, value-based weighting of the indicator results is permitted to be published. Therefore, the LCA practitioners should be aware that the normalisation or weighting may result in a biased conclusion; thus, they should be handled with extra care for the environmental declaration or comparison of products.

3.4. *Involvement of uncertainties*

The inherent uncertainties involved in the LCI database, methodology selection, system and scenario modelling, can highly affect the reliability of the LCA results. The final LCA result is not strictly objective, but decisively depends on the goal and definition of scope and the data quality from numerous input parameters. One may obtain a diverged result by applying different LCI data, methodology or functional unit. The LCA results may mislead the decision-makers without interpreting these uncertainties transparently. The significance of parameter changes should be well presented by the uncertainty analysis, which needs to be handled carefully to ensure that all the analyses are carried out under the same criteria. Several methods for uncertainty treatment, such as sensitivity analysis and Monte Carlo simulation, are frequently used by the LCA practitioners. However, uniform and reliable criteria are needed to explain the significance of the obtained results, or in what sense option A is better than option B. A standardised set of rules and guidelines for implementing LCA other than the ISO standards is highly needed.

4. State-of-the-art for LCA of bridges

Railway bridges are an important part of the transportation system in many countries worldwide; however, so far, their

Table 2. Summary of LCIA methodologies.

Method name	Considered category groups	Orientation level
Impact 2002 + http://www.sph.umich.edu/riskcenter/jolliet/downloads.htm The University of Michigan	Carcinogens, non-carcinogens, respiratory inorganic, ionising radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutri, land occupation, global warming, non-renewable energy and mineral extraction	Midpoint/endpoint level
ReciPe method http://www.lcia-recipe.net/	Fossil depletion, metal depletion, water depletion, natural land transformation, urban land occupation, agricultural land occupation, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, marine eutrophication, freshwater eutrophication, terrestrial acidification, climate change ecosystems, ionising radiation and particulate matter formations	Midpoint/endpoint level
CML 2007 http://cml.leiden.edu/software/data-cmlia.html Universiteit Leiden	Abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation	Midpoint level
TRACI http://www.epa.gov/nrmrl/std/sab/traci/ US Environmental Protection Agency	Global warming, acidification, carcinogens, non-carcinogens, respiratory effects, eutrophication, ozone depletion, ecotoxicity and smog	Midpoint level
Eco-indicator 99' http://www.pre-sustainability.com/content/eco-indicator-99/	Greenhouse effect, ozone layer depletion, ionising radiation, respiratory effects, carcinogensis, regional effect on vascular plant, local effect on vascular plant species, acidification, eutrophication and surplus energy for future extraction	Endpoint level
EPS 2000 http://www.cpm.chalmers.se/CPMdatabase/StartIA.asp Chalmers University of Technology	Life expectancy, severe morbidity, morbidity, severe nuisance, nuisance, crop growth capacity, wood growth capacity, fish and meat production, soil acidification, Prod. Cap. irrigation water, depletion of reserves and species extinction	Endpoint level
EDIP http://www.lca-center.dk/cms/site.aspx?p=378	Global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, eutrophication, ecotoxicity, human toxicity, persistent toxicity, hazardous waste, nuclear waste, slag and ashes, bulk waste and resource depletion	Endpoint level

Source: Barbara et al. (2009).

Table 3. LCA software.

Software name	Developer	LCI database	LCIA methods
ATHENA @Impact	The Athena Sustainable Materials Institute http://www.athenasmi.org	Building materials	TRACI
BEES v4.0	NIST, Building and Fire Research Department, USA http://www.bfrl.nist.gov/oae/software/bees	Building materials	n.a.
Boustead Model 5.0	Boustead consulting, UK http://www.boustead-consulting.co.uk/products.htm	Commonly used materials and processes	n.a.
CMLCA	Leiden University, the Netherlands http://www.cmlca.eu	n.a.	n.a.
ECO-it 1.4	Pré Consultants, the Netherlands http://www.pre.nl/eco-it/eco-it.htm	Commonly used materials and processes	Eco95' and Eco99'
EDIP PC Tool	Danish Environmental Protection Agency, Denmark	n.a.	EDIP
Economic Input–Output LCA	Carnegie Mellon University, USA http://www.eiolca.net	US NREL	n.a.
EPS 2000 Design System	Assess Ecostrategy Scandinavia AB http://eps.esa.chalmers.se/introduction.htm	Commonly used materials and processes	EPS
EQUER	École des Mines de Paris, France http://www-cep.ensmp.fr/francais/logiciel/indexequer.html	US NREL	n.a.
Envest 2	Envest, UK http://envest2.bre.co.uk/	n.a.	Ecopoints
GaBi 4 Software	PE International, IKP University of Stuttgart, Germany http://www.gabi-software.com/	Ecoinvent	Eco'95, Eco'99, Ecological Scarcity Method and CML
GEMIS	Öko-Institut, Germany, Global Emission Model for Integrated Systems http://www.oeko.de/service/gemis/en/index.htm	Commonly used materials and processes	CED
GREET Model	Transportation Technology R&D Center (TTRDC), USA http://www.transportation.anl.gov/modeling_simulation/GREET/index.html	n.a.	n.a.
IDEMAT	TU Delft, the Netherlands http://www.idemat.nl	Commonly used materials and processes	Eco'95, Eco'99, EPS and CExD
JEMAI-LCA	Japan Environmental Management Association for Industry, Japan http://www.jemai.or.jp/english/lca/project.cfm	n.a.	n.a.

Table 3 – *continued*

Software name	Developer	LCI database	LCIA methods
LCAiT 4	Chalmers Industriteknik, Ekologik, Sweden	Commonly used materials and processes	EPS, Eco-indicators, Environment theme method and EDIP
LCAPIX	KM limited, USA http://www.kmlmtd.com/pas/index.html	Boustead model, TELLUS, TME	EPS
SimaPro 7.3	Pré Consultants, the Netherlands http://www.pre.nl/simapro.html	Ecoinvent v2.2, ETH-ESU 96 database, BUWAL 250 and IDEMAT 2001	Eco'95, Eco'99, CMl 1992, CML 2000, EDIP, EPS 2000, Ecopoints 1997, EPD method, TRACI, Impact 2002+, CED and IPCC
SolidWorks	Dassault Systèmes SolidWorks Corp., http://www.solidworks.com/sustainability/sustainability-software.htm	n.a.	n.a.
TEAM™ 4.0 The Environmental Impact Estimator	Ecobilan, France https://www.ecobilan.com/uk_lcatool.php	Commonly used materials and processes	Eco'99, CML 2000 and IPCC
Umberto	Ifu Hamburg, Germany http://www.ifu.com/en/products/umberto	Ecoinvent	n.a.
WISARD	ECOBILAN https://www.ecobilan.com/uk_who.php	TEAM WISARD DEAM INES	n.a.
Simplified LCA	Simplified LCA software for railway bridge http://web.byv.kth.se/shared/pdf/3222_Report%20-%20V%20Thiebault.pdf	Ecoinvent	Streamlined approach
ETSI BridgeLCA	LCA software tool for Bridge http://www.tkk.fi/Yksikot/Silta/Etsiwww2/	Ecoinvent	CML2001

Source: Modified from Jönbrink et al. (2000), SAIC (2006) and Thiebault (2010).

Table 4. Comparison of weighting factors.

Impact categories	Unit	Normalisation factors				Weighting factors			
		Orig. EDIP 97	Global	EU-15	Denmark	Orig. EDIP 97	Global	EU-15	Denmark
Abiotic depletion	kg Sb eq./capita/year	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Acidification	kg SO_2 eq./capita/year	124	59	74	101	1.3	n.a.	1.27	1.34
Eutrophication	kg NO_3-eq./capita/year	298	95	119	260	1.2	n.a.	1.22	1.34
Global warming	ton CO_2-eq./capita/year	8.7	8.7	8.7	8.7	1.3	1.12	1.05	1.11
Ozone layer depletion	kg CFC-11 eq./capita/year	0.2	0.103	0.103	0.103	23	4.4	2.46	∞
Photochemical oxidation	kg C_2H_4-eq./capita/year	20	22	25	20	1.2	1.0	1.33	1.26

Source: Stranddorf et al. (2003).

environmental assessment has rarely been done and integrated into the decision-making process. It has been noticed that there are rather limited studies available for LCA of roadway bridges, but almost none for railway bridges. This section provides an explicit literature survey regarding the current available LCA study of the bridge structures. A number of emerged critical issues are identified and discussed below. The aim is to investigate and summarise the operational issues of implementing LCA for roadway bridges, thus, helping to establish a practical framework in a similar manner for railway bridges, which is further described below.

4.1. Literature survey

Widman (1998) compared two roadway bridges: a steel box-girder bridge with concrete decking in eight spans, and a steel I-girder bridge with concrete decking with single span, with implementing LCA through the whole life cycle. The scope of the study was focused on the substructure with pilings and the superstructure with railings and the deck surface. Marginal details of the joints and bearings are excluded. The data were collected from manufacturers in Sweden, Norway and Finland, and adapted to Swedish conditions. For comparison purpose, the studied unit was defined as environmental impact per square meter lane. The results indicated that the main sources of CO_2 emissions are from the manufacture of cement and steel. The concrete in steel bridges contributes to half of the environmental impact, and due to the fact that steel bridges need less material than concrete bridge, it can be concluded that steel bridges serve a good environmental choice. The vehicles carrying the material and products generate a large amount of the CO and NO_x emissions. It has been found the passenger traffic from the use phase of the bridge is the most polluting source, while the burden from the maintenance stage is ignorable.

Horvath and Hendrickson (1998) carried out an economic input–output-based LCA between a steel girder and a steel-reinforced concrete bridge girder through the whole life cycle, based on a publicly available database, with consideration of all the direct and indirect economic effects. The assessment was carried out for the life cycle stage of the material manufacture phase, use and maintenance phase and EOL phase. The results indicated that the steel-reinforced concrete bridge has a better environmental performance in the initial construction stage. However, from the whole life cycle perspective, steel girders are recyclable and more sustainable than the landfill of concrete design. It has been addressed that the analysis was limited due to lack of proper data.

Steele, Cole, Parke, Clarke, and Harding (2002) carried out LCA for brick arch bridges. The analysis was carried out by the software Simapro with default database combined with a UK-specific data profile The Building

Research Establishment (BRE). Ten environmental indicators were interpreted, which were further classified into three damage categories. Three life cycle stages as bridge construction, service life and structure strengthening are involved. The potential traffic disruption was assumed on the basis of structure location, vehicle flow rate, detour distance and structure closure time. The result indicated that the bridge initial material consumption represents the single biggest contributor to environmental impact, whereas the fill and mortar mixing generated ignorable impact. The maintenance has only minimal environmental impact when comparing with construction and traffic disturbance. Moreover, good maintenance extends the structure life that was regarded as a form of environmental saving. In spite of increased distance, transportation of materials to the sites accounts for minor environmental effect. That paper also addressed that constructing a saddle during the bridge strengthening process will have a high-environmental impact.

In the study by Steele, Cole, Parke, Clarke, and Harding (2003), a systems approach was applied for LCA modelling, with integrating LCA into the bridge maintenance strategy. The study was based on the review of 30 bridges with three material categories encompassing brick, reinforced concrete and steel bridge; the key maintenance activities and the accordance frequencies were investigated. The classification of bridge was categorised into the three forms of beam, arch and cable designs. The weighting procedure generated an environmental measurement scoring to rank the environmental performance either for whole life cycles, or for specific maintenance, refurbishment or strengthening strategies. The final conclusion recommended that the reduction of environmental impact should not be achieved at the expense of structure durability and longevity. The maintenance activities provide environmental saving due to deterioration prevention. The first objectives for all material disposals must be focusing on reuse and recycle of materials. To reduce both land take and transport demands, the inert material should be disposed on site.

Itoh and Kitagawa (2003) presented a comparative LCA between a conventional bridge (CB) and a minimised girder bridge (MGB) during the construction and the maintenance stage, in terms of the energy consumption and CO_2 emissions. The MGB is a new type of bridge with the concept of minimised maintenance activities and 100 years' service life. For each design alternative, three bridge types with 150 m length and 12 m width were chosen: Prestressed concrete (PC) simple pre-tensioned T-girder bridge, PC simple box-girder bridge and steel simple non-composite box-girder bridge. The result indicates that the steel bridge has the highest environmental impact value in comparison with other two PC bridges. And the manufacture of construction materials contributed to the largest environmental burden. The result indicated that MGB accounts for lower CO_2 emissions in each stage. The main girder, deck and pavement account for the major portion of CO_2 emissions for both bridge types. However, the CO_2 emission of the CB at the end of 120 years was higher than that of the MGB. The environmental impact differences can double when the service lives are between 60 and 100 years. It is also found that prolonging the service life of a bridge component is invaluable for both bridge types from the environmental perspective.

Martin (2004) discussed the sustainable issues in the context of concrete bridge, with several practical examples regarding how sustainable principles are being involved. One example showed the environmental comparison between a steel–concrete composite bridge deck and a concrete bridge deck, focused on the consideration of energy consumption and CO_2 emissions through the whole life cycle. The result indicates that when using the original materials, the concrete deck can generate 39% less energy and 17% less CO_2 emission; but when using the recycled materials, the steel–concrete deck alternative shows the advantage of 30% less CO_2 emissions, due to the benefits from steel recycling. Another example was carried out for the comparative study of the sustainable performance among three concrete types in a post-tensioned box-girder bridge deck: lightweight, normal density and high-strength concrete. However, in terms of life cycle energy, the result did not show that there are great advantages of any type of concrete over another.

Keoleian et al. (2005) applied a comparative LCA between two bridge deck systems over a 60 year service life. One deck system contains the conventional steel expansion joints, whereas the alternative system is a link slab using the engineered cementitious composite (ECC). ECC is an alternative promising material for extending the service life, with reduced maintenance activities. An LCI model of bridge deck system is developed based on ISO 14040 methods. The model includes the comprehensive life cycle from the material production phase, construction and maintenance processes, till the EOL. The analysis has considered the construction-related traffic congestion, and excluded the initial bridge construction process which is the same for both bridge deck systems. Several maintenance scenarios are assumed. The results of the LCA model indicate that the ECC bridge deck system has significant advantages for all pollutants categories. Compared with those of the conventional joints, the consumption of life-cycle energy for ECC is 40% less, the generation of solid waste is 50% less and the raw material consumption is 38% less. The construction-related traffic congestion is the greatest contributor to most life cycle impact categories.

Itoh, Wada, and Liu (2005) developed a life cycle approach for evaluating the environmental impact and the cost of the construction and maintenance stage of the bridge, with the consideration of its recovery after an earthquake. A steel bridge in the Japanese highway bridge system was presented as a case study. The use of materials and machinery of each operation is included in the construction stage, and only the painting was considered in the maintenance stage. The CO_2 emission was evaluated as the main pollutant and global warming indicator. It has been found that the environmental impacts and the cost of seismic risk mitigation vary with several uncertain parameters related to the earthquake hazard, which was ignored in the construction stage.

Collings (2006) compared the embodied energy and CO_2 emissions among three general bridge forms: cantilever, cable stayed and tied-arch bridges. Whereas for each bridge type, three alternative material groups were investigated, namely concrete, steel and steel–concrete composite bridge. For the construction phase, both CO_2 emission and the embodied energy consumption are studied; the estimated material quantities for each structural component are obtained from the geometric equilibrium method, other similar bridge type and the estimated loadings. For the maintenance phase, only CO_2 emissions were assessed, several maintenance scenarios were assumed. The approximate environmental burden of maintenance activities was calculated on the basis of component quantities, which were obtained from the construction process. Results indicated that the consumption of the embodied energy increases with the span length. The architectural solutions have a higher environmental burden for the same bridge forms. The CO_2 emission is almost the same for three bridge materials during the operation process. The maintenance-related CO_2 emission is slightly higher than during the construction process, which mainly accounts from the resurfacing activates. For the longer spans, concrete bridges are marginally better than the steel–concrete composites or all-steel structures. It also concluded that the CO_2 from the traffic diversion may vary significantly and dependent on the traffic volume, proportion of lorries and the diversion distance.

Lounis and Daigle (2007) suggested a life cycle-based approach for the design of concrete highway bridges, with emphasis on the reduction of CO_2 emissions, construction waste and life cycle cost. A comparative case study of concrete highway bridge decks was illustrated, designed with normal concrete and high-performance concrete (HPC) alternative. It has been found that the HPC leads to 30 years longer service life than the normal concrete alternative, since both the greenhouse gas emissions and the waste generation for the normal concrete deck alternative were three times higher than the HPC deck alternative, whereas the regulated maintenance alternative, the correlated traffic disruption and material consumption were the main attributing reasons. In other words, the HPC was found to benefit the environment due to reduced maintenance, minimised material consumption and waste generation.

Gervásio and Simões da Silva (2008) presented an integrated life cycle methodology of LCA and life cycle cost analysis, with the consideration of environment, economic, degradation and maintenance aspects. The integrated approach was further applied on a double I-girder steel–concrete composite bridge, with a comparison of a composite concrete–concrete U-girders bridge. In the LCA analysis, the case study was restricted only to the construction stage due to lack of data. The LCA was carried out based on the guidance of the ISO 14040 series. The impact assessment was implemented using the environmental problems approach, developed by the society for environmental toxicology and chemistry. The normalised data were obtained from the US EPA Office of Research and Development. Data of concrete production were obtained from the Portland Cement Association in the USA, whereas the data of steel production were derived from the International Iron and Steel Institute (IISI). The final environmental impact indicated that the steel–concrete composite solution provides a better environmental performance than the concrete solution.

Hammervold et al. (2009) developed an excel-based bridge LCA analysis tool on the basis of ISO 14040 standards and CML LCA methodology. The methodology was further implemented among three types of bridges through the whole life cycle: a 42.8 m Klenevågen steel box-girder bridge, 37.9 m Fretheim wooden arch bridge and 39.3 m Hillersvika concrete box-girder bridge. The study considered the main structural components, machinery construction equipments and a series of maintenance and EOL scenarios. It has been found that the material manufacture phase contributes to the highest environmental impact, whereas the impact from construction phase is marginal. The weighted result showed that the steel box-girder bridge is the worst environmental friendly solution, whereas the wooden arch bridge has the highest advantage in environmental performance. When obtaining the results in a unit surface area manner, the results differed from the whole bridge results, and the concrete solution became the most beneficial solution compared with the wooden bridge.

Horvath (2009) addressed several critical issues of applying the LCA in the bridge analysis. He claimed that the definition of a too narrow functional unit should be avoided, since two individual bridge components interact. In order to make an optimal decision, it is imperative to include a full life cycle from the planning and the design phase till the EOL. Furthermore, the location of the analysis also plays an important role, in terms of the local characteristics of labour, technologies and topographic information. He also highlighted the importance of the time horizon during the long lifespan of the bridge and a good LCA should quantify the widest range of environmental outputs instead of only greenhouse gases.

Bouhaya, Le Roy, and Feraille-Fresnet (2009) carried out an LCA for assessing the energy release and greenhouse gas emissions of a roadway bridge. The foundation and the superstructure equipment of barriers, sidewalk and pavement were excluded from the functional unit. The bridge is 25 m long wood structure combined with ultra high-performance concrete (UHPC), which is high strength and maintenance-free material. The scope of the study was defined for 100 years lifespan from production phase, construction phase and maintenance phase till EOL. For the production phase, the LCI environmental profiles for several types of products were obtained from several sources: environmental product declarations (EPD) for wood and IISI for steel. For the construction phase, the energy consumption and greenhouse emissions were counted for the *in situ* construction machinery. For the maintenance, the UHPC beam was regarded as a maintenance-free material, whereas the wood beams were assumed to be replaced during the service life. During the EOL, the demolition crane and several wasted treatment scenarios were considered. The result indicated that the highest environmental impact was due to the manufacturing phase. The high amount of repair work leads to low CO_2 emissions. The EOL scenario of wood as energy by heating emitted the largest amount of CO_2 but the least energy consumption. The high proportion of wood is preferable in terms of CO_2, which is largely related to the EOL scenarios.

Botniabanan (2010a, 2010b, 2010c, 2010d) provided four series of the EPD reports, which focused on the environmental impact assessment of the railway bridges of the Bothnia line in Sweden. The methodology followed the ISO 14040 standards, with a scope of the study confined on the superstructure of the railway bridge through 60 years' service life. The assessment considered the life cycle stage of the construction and maintenance phases, including series scenarios. The result indicated that the infrastructure material accounted for the largest share in the final environmental impact, which was followed by material transportation and construction work. However, no impact due to the category of ozone layer depletion was addressed. In terms of the resources consumption, wood is responsible for 100% contribution in the renewable materials, and solid rock 68.8% for the non-renewable materials, crude oil 52.9% for the non-renewable energy, hydro power 92.6% for the renewable energy and ferrous scrap 100% for the recycled resources.

Thiebault (2010) conducted a literature survey of the LCA for the transportation systems and LCA-related developments. Based on the survey, an excel-based LCA analysis tool for the railway bridge was developed. This tool was further implemented for comparing the environmental performance of two railway bridge designs of the Banafjäl Bridge: a steel–concrete composite railway bridge either with ballast design or with fixed-slab track design. It has been found that the environmental impacts of the fixed track alternative were lower than the ballast alternative among all the investigated impacts. The environmental burden from the raw material consumption was the major concern through the life cycle. The maintenance frequency and associated traffic disturbance assigned dominant effects for the bridge environmental performance.

Du and Karoumi (2012) suggested a framework for implementing the LCA into railway bridges; the framework was further illustrated on a case study of the Banafjäl Bridge in Sweden with two design options, by the CML 2001 method. The study was focused on the whole bridge, except the foundation, through its entire life cycle. Furthermore, sensitivity analysis was carried out regarding the parameter of maintenance scenarios variation, recycling rate changes and traffic disturbance considerations. 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, whereas the impacts from the construction machinery and material transportations can be ignored.

4.2. Discussion based on the literature survey

Bridges are complex structures, in which large amount of assumptions and simplifications are involved through the analysis. The quality of the final result is significantly affected by the level of detail of the input data, in terms of the structural location, life cycle scenarios, the selected LCIA method, implemented LCI database and the defined scope. Change of any of those mentioned parameters may lead to a biased result. Through the literature review, it has been found that the environmental profile of the structure is very case-specific and that one cannot draw a general conclusion for a certain type of bridge without carrying out the LCA study. For example, Hammervold et al. (2009) compared three bridge designs located in Norway, the result differed when using a unit surface area as a functional unit rather than by using the whole bridge, and the concrete solution became the most beneficial solution instead of the wooden bridge. Another example is Du and Karoumi (2012) who concluded that the material manufacture phase is the most dominant stage through the bridge life cycle, whereas Itoh and Kitagawa (2003) found it is the use phase instead. A further issue identified is how to categorise the life cycle stage of the bridge: should the transportation from factory to construction site belong to the manufacture stage or to the construction stage? Should the traffic be covered in the use phase of the bridge? Should the benefit from material recycling be counted in the current project, or in the next project where the recycled material will be used? Widman (1998) and Collings (2006) included passenger traffic in the scope of the study, which is very rarely done in other literatures. Itoh and Kitagawa (2003) combined the material manufacture stage with the construction stage into one stage for the analysis. Those issues are ambiguously defined from case to case through the literature review, which would affect the final conclusions and further comparisons among different cases.

Nevertheless, even for the same bridge, the scope of the study and considered life scenarios can be different, thus leading to a different conclusion. For example, Widman (1998) confined the scope by focusing on the substructure with pilings and the superstructure with railings and the deck surface. Bouhaya et al. (2009) excluded the foundation and the superstructure equipment of barriers, sidewalk and pavement in the analysis. The result would have been different if the scope is focused on the whole bridge. For another case, both Thiebault (2010) and Du and Karoumi (2012) carried out LCA on the same bridge, the Banafjäl Bridge. The analysis was different from several aspects, since Thiebault (2010) used 'total bridge superstructure during 60 years' lifespan' as the functional unit, with the Eco-indicator 99' LCIA method, the result from both the inventory level and the potential impact level was presented; whereas Du and Karoumi (2012) used '1 meter bridge in the longitudinal direction during 120 years' lifespan', with the CML 2001 as LCIA method, the results were focused on the comparison from the environmental impact allocation of each structural component, as well as the total impact comparison for each life cycle stage. The obtained results in each paper focused on different aspects, thus cannot be compared directly, even though both finally concluded that the fixed slab option shows better environmental performance.

Furthermore, through the literature review, it has been found that most case studies cannot be explicitly carried out due to the lack of data, such as in Horvath and Hendrickson (1998) and Gervásio and Silva (2008), whereas almost all the other investigated cases more or less adopted the LCI data from another case study or from average database instead of using the realistic data. As mentioned earlier, the LCI data of the materials largely depend on the location and the specific processing technology, although a number of commercial LCI databases are available, the realistic data from the factory are always preferable rather than the global average data. Moreover, the necessary information is usually hard to obtain or predict, such as the realistic maintenance scenarios, the associated material quantities and activity intervals, instead, those information are obtained either from other similar cases, or from assumptions, or even omitted in the study. For instance, due to lack of information, Horvath and Hendrickson (1998) omitted the analysis of the construction stage; Itoh and Kitagawa (2003) excluded the material manufacture and EOL stage; Itoh et al. (2005) considered painting as the only scenario in the maintenance stage; Gervásio and Silva (2008) carried out the study only for the construction stage; Widman (1998) adjusted the LCI data from Finnish and Norwegian condition to a Swedish condition. Instead of the realistic maintenance schedule, Collings (2006) roughly estimated the environmental burden of maintenance activities from the component quantities during the construction process. Finally, in order to obtain reliable results, realistic information of bridge conditions should be used.

Lack of uniform LCA guidelines and criteria is recognised as another important issue:

(1) Various LCIA methods and LCI databases are developed. However, the presentation of final results is very dependent on the selected methodology and the definition of the scope of the study, which cause difficulties for comparison. For example, Widman (1998) obtained different results based on three LCIA methods: EPS method, Environment theme method and Ecoscarcity method. Thiebault (2010) and Du and Karoumi (2012) carried out the study by using the Eco-indicator 99' method and CML 2001 method separately. In order to make a comparable study, a standardised set of rules and guidelines is needed to specify the operational principles.
(2) A set of proper criteria is highly needed to illustrate what are the qualified limits of a bridge to fulfil the environmental requirements, what impact categories should be included in the criteria to judge whether the performance of one bridge is better than another. Moreover, it has been found that most of the reviewed publications were on the emission of CO_2 and energy rather than on a complete LCA with a full list of impact categories. For example, for explaining the GWP, most investigated cases are on CO_2 emissions and the emission of N_2O and CH_4 are simply omitted. Moreover, Thiebault (2010) and Du and Karoumi (2012) carried out LCA study on the same bridge based on different methodologies, scope of the study and target emissions. In particular, Thiebault (2010) described emissions of CO, CO_2, CH_4, NO_x, SO_2, non-methane volatile organic compounds (NMVOC) and PM10, whereas Du and Karoumi (2012) focused on result from the category of abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP100), ozone layer depletion potential (ODP) and photochemical oxidation potential (POCP). Since the results are presented in different levels, different studies cannot be compared directly.
(3) How the material quantities of the bridge are calculated is mostly not mentioned in the investigated literatures. The structural components and material types involved in each stage are trivial, but can significantly affect the environmental performance in a life-cycle manner. For the reason of

comparison, the scope of calculation should be consistent to the same level among different studies. Some studies in the literature estimated the material quantities through theoretical methods instead of realistic calculation. For instance, Collings (2006) estimated the material quantities by the geometric equilibrium method; Thiebault (2010) calculated on the basis of mathematical models presented in Finnish Road Administration (2001), based on a survey of up to 500 road bridges designed between 1990 and 2003.

The type of material and structure design can largely affect the final environmental performance of the bridge. For instance, Lounis and Daigle (2007) and Keoleian et al. (2005) concluded that high-durable material benefit the environment due to reduced maintenance, minimised material consumption and waste generation. Thiebault (2010) and Du and Karoumi (2012) found that the fixed-slab track has lower environmental impact in several categories than the ballast track. The designer should avoid using the structural components that require frequent maintenances. Du and Karoumi (2012) also pointed that the steel and reinforcement were the main environmental contributors through the life cycle. In general, steel and reinforcement have larger embodied energy than the concrete in the initial manufacture stage, but the recycling and reuse in the EOL often benefits the final performance. For real-life applications, an LCA study is required for selecting the particular material and bridge type.

5. Railway bridge LCA framework

So far, the implementation of the LCA approach in roadway or railway bridge infrastructures is very scarce. Due to limited research, most of the case studies are done without following a generally accepted methodology or framework, whereas they only emphasise on a few emission types and part of life cycle. In order to provide a generalised LCA framework of railway bridges to the practitioner and decision-maker, this paper explicitly reviewed the current available LCA studies for bridge structures, including 14 for roadway bridges and 4 for railway bridges, with the intention to partially combine the LCA knowledge from the roadway bridges with railway bridges. The railway bridges differ from the road bridges in several aspects, including the structural component, construction technique, maintenance and EOL scenarios. Finally, a systematic LCA framework is developed and suggested for modelling the whole life cycle of the railway bridge infrastructures, as illustrated in Table 5.

This suggested framework can be implemented as a guideline, either for the whole railway bridge or for a specific life cycle stage or part of the structural components. Each bridge element is covered from the railway track to the superstructure and substructure, with the components associated with a certain material type. The LCI data with the detailed manufacture procedures and known scopes, which are discussed earlier, would be linked with the selected material. The selected LCIA method is further assigned to the inventory data in accordance with the ISO standards. The results can be presented in terms of specific impact damage indicators for the human health, ecosystem and resource depletions. The recommendations of a broad set of specific life cycle stages for the railway bridge are described below.

5.1. *Material manufacture phase*

This phase takes into account the material manufacture and distributions from the raw material extraction until the products are ready to the construction site. This stage itself may compose a whole life cycle of material production, with the involvement of a series of activities from raw material extraction, sub-material transportation, energy consumption till the waste treatment. As listed in Table 6, railway bridges consist of enormous complex structures and a wide range of material types. It has been found that the final environmental performance largely relies on the selection of material types, which is a key factor further affecting the necessary consumption quantity, on-going maintenance schedules and EOL scenarios. The embodied environmental profile of each material is dominated by the constituted raw materials, manufacture technology and the supply chains. Each of these mentioned processes can be illustrated by a long list of LCI data. The LCI data are often provided by the commercial databases, with known scope of study and the unit embodied environmental profile linking to each material type. Although a large number of LCI databases are available, they still do not cover all of the material types in reality. The reliability and accuracy of the final analysis result is limited to the selected LCI database; thus, the site-specific LCI data are always preferable than the average data from the commercial databases.

5.2. *Construction phase*

Since there are several widely used methods for the construction stage of bridges, each of the techniques may lead to different energy efficiency in the construction machine, which would further affect the environmental performance. From the literature survey, it has been found that this phase is often omitted or roughly estimated in practical cases. The construction phase focuses on a wide range of operational systems, including electricity consumption, material transportation at site, energy consumption from the construction machinery, establish-

Table 5. The main parameters to be considered for the LCA of railway bridges.

Phase	Parameters
Material manufacture phase	**Bridge type**: Concrete bridge, Steel bridge, Composite bridge, Timber bridge → **Structural components**: Railway track system, Superstructure, Substructure, Foundation → **Material and Energy**: Concrete, steel, painting, timber, rubber, aggregate, electricity, reinforcement, fuel Initial material and energy consumption
Construction phase	Energy consumptions of construction machines Scaffoldings construction Traffic disturbances
Maintenance and use phase	**Maintenance schedules with related traffic disturbances and transportation** (see below) Energy consumptions of construction machines Traffic disturbances
End of life phase	Bridge demolition, material sorting, transportations Energy consumptions from the construction machines Concrete crushing, steel recycling, waste landfill

Maintenance schedules with related traffic disturbances and transportation

Structural	Maintenance activity	Ballast track	Fixed-slab track
Railway track	Rail grinding	1 year	1 year
	Track direction	0.5 year	no repair
	Rail replacement	25 years	25 years
	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
	Structural strengthening, patching and replacement	----	-----

↓ **LCI database**

Releases to water, air and solid
ammonia, benzene, carbon monoxide, nitrogen oxides, sulphur oxides, hydrogen chloride, hydrogen fluoride, hydrogen sulphide, carbon dioxide, dinitrogen monoxide, methane, NMVOC, etc.

→ **LCIA method**
ReCiPe, CML, Eco-indicator 99', EDIP 2003', EPS 2000', Impact 2002+, TRACI, IPCC, etc.

→ **Impact categories**
Abiotic Depletion Potential, Acidification Potential, Eutrophication Potential, Global Warming Potential, Ozone Layer Depletion Potential, Photochemical Oxidation Potential, etc.

ment of associated scaffoldings and supporting systems. The type of construction machine varies from earthwork cranes, forklift trucks, excavators on site, soil compactor, excavator and related transportations. However, the information of these operational machineries is usually unavailable from the contractor, or is hard to estimate in the early project stage. In order to better promote the sustainability development for bridges, the authority should require the company to build a project-level based database system for construction information.

5.3. *Maintenance and use phase*

This phase is the longest life stage, which is responsible for a large proportion of environmental burdens due to replacing of the structural components and related traffic disturbances. One challenging issue in this phase is to fairly predict the future maintenance schedules and activity intervals, which involves large inherent uncertainties. Table 5 recommends a series of maintenance activities for railway bridges by Tirus, H., Andersson, A. and Prokopov A. (21 December 2010. Personal contact by email, Trafikverket, Sweden.) As in all

Table 6. Example of considered structural elements of the railway bridge.

Structure	Structural element
Foundation	Piles, embankment and abutment
Load-bearing structure	Slab, beam, truss, arch, cable, bracing, steel girder, frame and painting
Railway track	Rails, sleepers, fixed-slab track, ballast track, rail fasteners and rail pads
Bridge equipment	Dehumidification machine, railing, parapet, bearing and joints
Earthwork	Drainage, excavation and landfill

maintenance tasks, there are several common repair tasks that apply to almost all bridges despite the materials used in construction; repairs can involve strengthening, replacing or adding support to the existing components (ARMY TM 5-600, 1994). So far, the estimations are mostly governed by the historical data or the engineering sense of experiences. Besides, the realistic maintenance or repair activities such as structural strengthening and component replacement are influenced by the design type, service life, train loading, infrastructure durability, periodic inspection and the budget plans. Due to the uncertainties, a further sensitivity analysis is imperative for testing the influence from the significance of each scenario. Different design solutions also affect the maintenance scenarios, which further influence the environmental performance. Due to the single-track design, most of the maintenance activities require a traffic closure that cause extra environmental burdens. The high-quality materials have been proved to efficiently prolong the service life and improve the environmental performances in a long term.

5.4. *EOL phase*

This phase concentrates on the energy consumption from the demolition, recycling processes and involved transportations. With an attempt to model the future waste treatment scenarios based on today's technologies, the EOL covers a series scenarios of bridge demolition, waste sorting, material reuse or recycling, incineration and final landfill. In general, the material recycling and waste treatment in the EOL stage are expected to benefit the environment, in terms of producing the co-products and energy, recycling and reuse of materials. In practice, the environmental benefits from EOL are quantified in the next project in which the recycled material is in use. Concrete, aggregate, reinforcement and steels are the basic materials in bridges, from which the metal of ferrous iron, zinc and aluminium are 100% recyclable without losing original properties. From the construction plate and beams, the steel recycling rates were up to 88% (Fenton & Reston, 1998). The environmental benefits due to the steel recycling during the processing can be quantified by the avoided burden method. Besides, the concrete is commonly crushed and reused as lower quality aggregates in road, whereas the aggregates can be either reused or crushed into the backfills if not contaminated. The selection of EOL strategies is imperative for the final environmental performance of the bridge, which may potentially eliminate environmental burdens.

6. Conclusions

This article provided a detailed literature survey regarding the current developments inherent in the LCA for bridges. A systematic LCA framework for railway bridges was also developed, as a potential guideline for the practitioners and the decision-makers. This framework presented a general procedure for quantifying the emissions and energy consumptions through the railway bridge life cycle. Several associated practical issues regarding state-of-the-art in LCA were discussed. The LCA implementation into railway bridges is under high expectation to set new design criteria, optimise the design and assist the decision-making process among different design proposals.

(1) Lack of uniform LCA guidelines and criteria is recognised as a main obstacle. It has been found that a unified set of criteria is highly needed to illustrate what are the qualified limits of a bridge to fulfil the environmental requirements, what impact categories should be included in the guidelines to judge whether one bridge is better performed than another. Due to the complex nature of the environmental science, different assessment approaches are developed for various typology conditions. Although this enables the practitioner to choose among a wide range of LCIA methods and LCI databases, the final results are proved to be very dependent on the chosen methodologies, data and the goal and scope definitions. The comparison of results and product declaration should thus be handled carefully to ensure LCA analyses are done under the same scope level. Commercial LCA software enables the practitioner to choose from a variety of LCIA methods, and the explanation for a specific choice can be given as: 'method A is different from method B since it emphasises on different emission inventory groups'. However, different LCA results become incomparable when utilising inconsistent data and methods. In practice, the principle for selecting the best probable LCIA method is the tendency to adopt the newest method available.

(2) Another important issue in LCA is the availability of LCI data and the project-related information. It has been noticed that many case studies are

inexplicitly carried out due to the limitation of data. On one hand, LCI data of material largely depend on the location and specific processing technologies. Even though a number of commercial LCI databases are available, the realistic data from the factory are always preferable than the global average data. The variety of existing LCI databases may give a biased or diverse result even for the same case study. On the other hand, necessary information is usually hard to obtain, such as the realistic construction, maintenance, EOL scenarios and the associated activities. Instead, the information are either obtained from other similar cases, or based on assumptions, or even omitted in the study. In order to ease the LCA implementation, a full access to the information of bridge life cycle scenarios is required. The authority should promote the establishment of a project-level-based database system for the construction information.

(3) The inherent uncertainties involved in the LCI database, methodology selection, system and scenario modelling can significantly influence the reliability of the LCA results. The change of any of the above-mentioned factors may lead to a biased result. Through the literature review, it has been found that the environmental profile of the structure is very case-specific and that one cannot draw a general conclusion for a certain type of bridge without carrying out the LCA study. The transparent illustration of the operational procedure can improve the reliability of the result. For instance, Hammervold et al. (2009) compared three bridge designs, when using a unit surface area as a functional unit rather than a whole bridge; the concrete solution then became the most beneficial solution instead of the wooden bridge. Moreover, due to varying input parameters and the scope of the study, the LCA results, even for the same bridge, cannot be compared directly [e.g. for Banafjäl Bridge studied by Thiebault (2010) and Du and Karoumi (2012)]. In addition, the LCA results may mislead the public when they do not interpret clearly the uncertainties involved. Thus, the significance of parameter changes should be well evaluated by the uncertainty analysis. Moreover, the practitioner should also be aware of the biased results caused from normalisation or weighting, which should be handled carefully for the environmental declaration or for the products comparison purpose.

(4) The application of high quality and durable materials with enhanced structural capacity shows prominent advantages. Apart from the initial material manufacture stage, the maintenance stage has been identified as the longest and most influential stage through the life cycle. The individual design with reduced maintenance activities, which can further decrease material consumption and waste generations, is highly recommended. It is thus proposed for the designer to utilise the structural component with suitable maintenance solutions, such as less small components of expansion joints, bearings or painting. For instance, Lounis and Daigle (2007) and Keoleian et al. (2005) pointed that high-durable material benefits the environment due to reduced maintenance, minimised material consumption and waste generations. In the case study of the Banafjäl Bridge by Thiebault (2010) and Du and Karoumi (2012), due to the improved maintenance strategy and the less material consumption, it was shown that the fixed-slab design gives better environmental performance than the ballasted design.

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