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

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ABSTRACT: Currently the whole world is confronted with great challenges related with 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, while the environmental assessment is rarely integrated. Life cycle assessment (LCA) is deemed as a systematic method for assessing also 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.

Key words: 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 is responsible for 88% of greenhouse gases, in contrast to 12% by the train operation and rolling stock. Moreover, UITC (2009) pointed that, in comparison to the train operation and rolling stock, the infrastructures in the European Railway Network can account for 9% up to 85% CO₂ equivalent emissions, that 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 waterborne transport by 2050, which will simultaneously require the increase of railway networks (Europa 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 life span. Up to 2012, the Swedish authority owns 3842 railway bridges and 145 tunnels over 13642 km railway tracks (Erbén L., 28th May, 2012. Personal contact by email. Trafikverket, Sweden). However, most of their current environmental assessments are only performed for the 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, 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 assessment for railway bridges is still new, lacking of international

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 life span.

Due to those considerations, this paper 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 either for the LCA limitations or the appeared operational issues. Based on these, a theoretical LCA framework for railway bridges is to be introduced, with 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 standardized 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 70s. The international standards ISO 14040 and ISO 14044 are available for LCA, however, it has been realized that they were only developed for general guidance purposes rather than for practical specifications (Fava, 2011), thus, lack of 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.

Goal and scope 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 study scope, the purpose and assumptions should be addressed clearly, as well as the inclusion of life span 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).

Life cycle inventory phase: The life cycle inventory (LCI) takes account of the inputs and outputs related with 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 manufacture factory, government, commercial databases, and scientific journals.

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 consist of several sub-processes of classification and characterization, and optional sub-processes of normalisation, grouping and weighting (ISO 14044, 2006):

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

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

Normalisation: This optional step compares the characterized 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.

Grouping and weighting: These are two optional steps for easing the interpretation procedure. The step of grouping sorts and ranks the characterization results into several sets, such as global/regional/local or

high/medium/low; while weighting evaluates the relative importance of each impact category among all the other based on the political and society evaluation (Baumann and Tillman, 2001).

Interpretation: Interpretation refines the numerous LCA results into specific explanation with meaningful conclusions. ISO 14040 defines that in the interpretation phase of life cycle assessment 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 and Notten (2006), Table 1 provides an overview summary of LCI database that emphasises on the construction field, with the condition adjusted to a 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 a LCA study; i.e., the manufacture technologies of each material differ from one region to another, even the same material may have varying environmental profile 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 perform uncertainty analysis is 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 interview, realistic LCI data provided by the manufacturer is 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 as 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 to the ISO standards. Table 2 presents the example of impact indicators considered in different LCIA methodologies based on Barbara et al. (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, etc) and stressed that each of them emphasizes particularly either on the midpoint level or the end point 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 the selected method. A certain impact category may be significant in one LCIA method, while it can be negligible in another method; for example, the category of Abiotic depletion (ADP) is included in CML method but excluded in TRACI method; category of carcinogens and non-carcinogens are 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 bio-fuels, they 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 up 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, while 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 in the work of Jönbrink *et al.* (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 *et al.*, 2009) that are recently developed in the Nordic countries, which are specialized for bridge analysis. Due to the complexity of the railway bridge structures and long life span, none of the current LCA tools can provide the 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.

3.3 Arbitrary results due to normalisation and weighting

Normalisation and weighting are optional steps within LCIA process. Normalisation compares the actual characterisation results with the reference ones; while 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 *et al.* 2003), while the category of Global warming potential updated from 8.7E+03 kg CO₂ eq/person/year in EDIP97 to 7.7E+03 in EDIP2003 (Laurent *et al.* 2011). Since there is no societal consensus on these fundamental values, there is no reason to expect consensus either on weighting factors or on the weighting method, or even on the choice of using a weighting method at all (Finnveden, 1999). Moreover, the ILCD 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 modeling, can highly affect the reliability of the LCA results. The final LCA result is not strictly objective, but decisively depends on the goal and scope definition 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 performed 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 standardized set of rules and guidelines for implementing LCA other than the ISO standards is highly needed.

Table 1. Life cycle inventory databases.

Database name	Managed by	Description
Life Cycle Inventory of Portland Cement Concrete	Portland cement association PCA R&D Serial No. 3011 http://assets.ctlgrou.com/aca962c9-279b-4cf2-9dac-9706094e408e.PDF	The life cycle inventory (LCI) of ready mixed concrete, concrete masonry, and precast concrete.
World steel Life Cycle Inventory	Former IISI (International Iron and Steel Institute) 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.
U.S. database	US National Renewable Energy Laboratory (NREL) http://www.nrel.gov/lci/	Various material, energy and assembly in the U.S. 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 in report for the road construction material for the Swedish condition.
Zygomalas et. al. (2010)	http://dx.doi.org/10.1080/15732479.2010.519711	A newly developed life cycle inventory (LCI) database for commonly used structural steel components.

Table 2. Summary of LCIA methodologies (Barbara et al., 2009).

Method name	Considered category groups	Orientation level
Impact 2002+ http://www.sph.umich.edu/riskcenter/joliet/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, 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, 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, Fresh water aquatic ecotox., marine aquatic ecotoxicity, Terrestrial ecotoxicity, Photochemical oxidation.	Midpoint level
TRACI http://www.epa.gov/nrmrl/std/sab/traci/ U.S. Environmental Protection Agency	Global warming, Acidification, Carcinogens, Non-carcinogens, Respiratory effects, Eutrophication, ozone depletion, Ecotoxicity, Smog.	Midpoint level
Eco-indicator 99' http://www.pre-sustainability.com/content/eco-indicator-99/	Greenhouse effect, Ozone layer depletion, Ioniz. Radiation, respiratory effects, carcinogenesis, regional effect on vascular plant, local effect on vascular plant species, acidification, eutrophication, 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, 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, resource depletion.	Endpoint level

Table 3. LCA software (modified from Jönbrink et al., 2000; SAIC, 2006; Thiebault, 2010).

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, US http://www.bfrl.nist.gov/oac/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, Netherlands http://www.cmlca.eu	n/a	n/a
ECO-it 1.4	Pré Consultants, Netherlands http://www.pre.nl/eco-it/eco-it.htm	commonly used materials and processes	Eco95', Eco99'
EDIP PC Tool	Danish Environmental Protection Agency, Denmark	n/a	EDIP
Economic Input-Output LCA	Carnegie Mellon University, US http://www.ciolca.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/index-equer.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, 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), US http://www.transportation.anl.gov/	n/a	n/a

	modeling_simulation/GREET/index.html			
IDEMAT	TU Delft, 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
LCAiT 4	Chalmers Industriteknik, Ekologik, Sweden	commonly used materials and processes		EPS, Eco-indicators, Environment theme method, EDIP
LCAPIX	KM limited, US http://www.kmlmtd.com/pas/index.html	Boustead model, TELLUS, TME		EPS
SimaPro 7.3	Pré Consultants, 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, 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_lcato.php	commonly used materials and processes		Eco'99, CML 2000, 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

Table 4. Comparison of weighting factors (Stranddorf *et al.* 2003).

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 ₂ H ₄ -eq./capita/year	20	22	25	20	1.2	1.0	1.33	1.26

4. State of the art for LCA of bridges

Railway bridges are important part of the transportation system in many countries worldwide, however, so far, their environmental assessment has rarely been performed 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 in below. The aim is to investigate and summarize the operational issues of implementing LCA for roadway bridges, thus, helping to establish a practical framework in a similar manner for railway bridges, which will be further described in this article.

4.1 Literature survey

Widman (1998) compared two roadway bridges: a steel box girder bridge with concrete decking in 8 spans, and a steel I-girder bridge with concrete decking with single span, with implementing LCA through the whole life cycle. The study scope 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 are collected from manufactures in Sweden, Norway and Finland, with adaption to Swedish conditions. For comparison purposes, the studied unit is environmental impact per square meter lane. The results indicated that the main sources of the CO₂ emissions are caused from the manufacture of cement and steel. The concrete in steel bridge contributes to half of the environmental impact, and the fact that steel bridge needs less material than concrete bridge, conclude that steel bridge serves 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 stage, while the burden from the maintenance stage is ignorable.

Horvath and Hendrickson (1998) performed an economic input-output based life cycle assessment (EIO-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 is performed 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, the steel girders are recyclable and more sustainable compare with the landfill of concrete design. It has been addressed that the analysis was limited due to lack of proper data.

Steele et al. (2002) performed life cycle assessment for brick arch bridges. The analysis was performed by the software Simapro with default database combined with a UK specific data profile 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; while the fill and mortar mixing generated the ignorable impact. The maintenance has only minimal environmental impact when comparing with construction and traffic disturbance. Moreover, good maintenance extends the structure life that regarded as a form of environmental saving. In spite of

increased distance, transportation of materials to the sites accounts for minor environmental effect. The paper also addressed that constructing a saddle during the bridge strengthening process will have a high environment impact.

In the study by Steele et al. (2003) a systems approach was applied for the LCA modeling, with integrating LCA into the bridge maintenance strategy. The study was based on the review of 30 bridges with 3 material categories encompassing brick, reinforced concrete and steel bridge, the key maintenance activities and the accordance frequencies were investigated. The classification of bridge was categorized 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 the 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 minimized girder bridge (MGB) during the construction and the maintenance stage, in terms of the energy consumption and CO₂ emissions. The MGB is a new type bridge with the concept of minimized maintenance activities and 100 years' service life. For each design alternative, three bridge types with 150 m length 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 the steel bridge has the highest environmental impact value in comparison to other two PC bridges. And the manufacture of construction materials contributed to the largest environmental burden. The result indicated that MGB accounts for lower CO₂ emissions in each stage. The main girder, deck, and pavement accounts for the major portion of CO₂ emissions for both bridge types. However, the CO₂ emission of the CB at the end of 120 years was higher than those 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 been 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 CO₂ 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 CO₂ emission; but when using the recycled materials, the steel-concrete deck alternative shows the advantage of 30% less CO₂ 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 among: lightweight, normal density and high-strength concrete. However, in terms of life-cycle energy, the result didn't show that there are great advantages of any type of concrete over another.

Keoleian et al. (2005) applied a comparative life cycle assessment (LCA) between two bridge deck systems over a 60 years' service life. One deck system is containing the conventional steel expansion joints, while the alternative one 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. A life cycle inventory 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, while excluded the initial bridge construction process which exists the same for both bridge deck systems. Several maintenance scenarios are assumed. The results of LCA model indicate that: the ECC bridge deck system has significant advantages for all pollutants categories. Compare to the conventional joints, the consumption of life cycle energy for ECC is 40% less, the generation of solid waste decrease 50%, and the raw material consumption is 38% less. The construction related traffic congestion is the greatest contributor to most life cycle impact categories.

Itoh et al. (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 are included in the construction stage, and only the painting was considered in

the maintenance stage. The CO₂ 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 CO₂ emissions among three general bridge forms: cantilever, cable stayed and tied-arch bridges. While for each bridge type, three alternative material groups were investigated, namely concrete, steel and steel-concrete composite bridge. For the construction phase, both CO₂ 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 CO₂ emissions were assessed, several maintenance scenarios were assumed. The approximate environmental burden of maintenance activities were 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 CO₂ emission is almost the same for three bridge materials during the operation process. The maintenance related CO₂ emission is slightly higher than the construction process, which is mainly accounts from the resurfacing activates. For the longer spans concrete bridges are marginally better than the steel-concrete composites or all-steel structures. The CO₂ 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 CO₂ 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 compared with 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, while the regulated maintenance alternative, the correlated traffic disruption and material consumption were the main attributed reasons. In other words, the high performance concrete was found to benefit environment due to reduced maintenance, minimized material consumption and waste generation.

Gervásio and Simões da Silva (2008) presented an integrated life cycle methodology of life-cycle assessment (LCA) and life cycle cost analysis (LCCA), 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 life-cycle assessment (LCA) was performed 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 (SETAC). The normalized 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 US, while the data of steel production were derived from the International Iron and Steel Institute. 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 meters Klenevågen steel box-girder bridge; 37.9 meters Fretheim wooden arch bridge and 39.3 meters 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, while the impact from construction phase is marginal. The weighted result showed that the steel box girder bridge is the worst environmental-friendly solution, while the wooden arch bridge has the highest advantage in the 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 to the wooden bridge.

Horvath (2009) addressed several critical issues of applying the life-cycle assessment 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 the labor, technologies and topographic information. He also highlighted that the importance of the time horizon during the long life span of the bridge, a good LCA should quantify the widest range of environmental outputs instead of only greenhouse gases.

Bouhaya et al. (2009) performed a life cycle assessment 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 length wood structure combined with ultra high performance concrete (UHPC), which is high strength and maintenance free material. The study scope was defined for 100 years life span 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: EPD for wood and International Iron and Steel Institute (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 while the wood beams were assumed to be replaced during the service life. During the EOL, the demolition crane and several waste 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 CO₂ emissions. The EOL scenario of wood as energy heating emitted the largest amount of CO₂ but the least energy consumption. The high proportion of wood is preferable in terms of CO₂, which is largely related to the EOL scenarios.

Botniabanan (2010a, b, c, d) provided four series of the Environmental Product Declarations (EPD) reports, which focused on the environmental impact assessment of the railway bridges of the Bothnia line in Sweden. The methodology was followed by the ISO 14040 standards, with a study scope 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 the material transportation and construction work. However, no impact due to the category of ozone layer depletion was addressed. In terms of the resources consumption, the 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, the sensitivity analysis was performed 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, while the impacts from the construction machinery and material transportations can be ignored.

4.2 Discussion based on the literature survey

Bridges are complex structures, that large amount of assumptions and simplifications are involved through the analysis. The quality of final result is significantly affected by the detail level of the input data, in terms of the structural location, life cycle scenarios, the selected LCIA method, implemented LCI database and the defined scope. The change of any those mentioned parameters may lead to a biased result. Through the literature review, it has been found the environmental profile of the structure is very case specific, that one cannot draw

a general conclusion for a certain type of bridge without performing the LCA study. For example, Hammervold et al. (2009) compared three bridge design located in Norway, the result differed when using a unit surface area as a functional unit other 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) concluded the material manufacture phase is the most dominant stage through the bridge life cycle while Itoh and Kitagawa (2003) found it is the use phase instead. A further issue has been identified is how to categorize the life cycle stage of the bridge: should the transportation from manufactory to construction site belong to manufacture stage or 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 study scope, while very rarely performed in other literatures. Itoh and Kitagawa (2003) combined the material manufacture stage with the construction stage into one stage over the analysis. Those issues are found ambiguously defined from case to case though the literature review, thus would affect the final conclusions and the further comparisons among different cases.

Nevertheless, even for the same bridge, the study scope and considered life scenarios can be different, thus lead to a varied conclusion. For example, Widman (1998) confined 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 focusing on the whole bridge. For another case, both Thiebault (2010) and Du and Karoumi (2012) performed LCA on the same bridge of the Banafjäl Bridge. The analysis were different from several aspects, since Thiebault (2010) used 'total bridge superstructure during 60 years life span' as the functional unit, with the Eco-indicator 99' LCIA method, presented the result from both the inventory level and the potential impact level; while Du and Karoumi (2012) used '1 meter bridge in the longitudinal direction during 120 years life span', 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 were focusing on different aspects, thus cannot be compared directly, even though they both finally concluded the fixed slab option shows the better environmental performance.

Furthermore, through the literature review, it has been found most case studies cannot be explicitly performed due to the lack of the data, such as in Horvath and Hendrickson (1998), Gervásio and Silva (2008); while 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 manufacture factory is always preferable rather than those 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 either obtained 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 (2003) excluded the material manufacture and EOL stage; Itoh et al. (2005) only considered painting as the only scenario in the maintenance stage; Gervásio and Silva (2008) performed the study only for the construction stage; Widman (1998) adjust the LCI data from Finnish and Norwegian condition to a Swedish one. 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 recognized 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 study scope, 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) performed the study by using Eco-indicator 99' method and CML 2001 method separately. In order to make a comparable study, a standardized 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 fulfill the environmental requirements, what impact categories should be included in the criteria to judge if one bridge is better performed than another. Moreover, it has been found that most of the reviewed publications are carried out only for the emission of CO₂ and energy other than a complete LCA with a full list of impact categories. For example, for explaining the global warming potential, most investigated cases are presented in terms of the CO₂ emissions, that the emission of NO₂, CH₄, and CFCs are simply omitted. Moreover, Thiebault (2010) and Du and Karoumi (2012) performed LCA study on the same bridge based on different methodology, study scope and target emissions. In particular, Thiebault (2010) described emissions of CO, CO₂, CH₄, NO_x, SO₂, NMVOC, and PM10, while Du and Karoumi (2012) claimed 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 level, different studies cannot be compared directly.

3) How the material quantities of the bridge be calculated are 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 comparison reason, the calculation scope should be consistent to the same level among different studies. Some studies in the literature estimated the material quantities through theoretical method instead of realistic calculation, For instance, Collings (2006) estimated 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 (2005) concluded that high durable material benefit the environment due to reduced maintenance, minimized material consumption and waste generation. Another case is, Thiebault (2010) and Du and Karoumi (2012) found that the fix-slab track has lower environmental impact in several categories comparing with 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 contributor through the life cycle. Generally, steel and reinforcement has larger embodied energy comparing with the concrete in the initial manufacture stage, but the recycling and reuse in the EOL often benefits the final performance. For real-life applications, a LCA study is required for selecting the particular material and bridge type.

5. Railway bridge life cycle assessment framework

So far, the implementation of LCA approach into roadway or railway bridge infrastructures are very scarce. Due to limited research, most of the case studies are performed without following a generally accepted methodology or framework, while only emphasized on a few emission types and part of life cycle. In order to provide a generalized 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 modeling 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 associating with a certain material type. The

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

Material manufacture phase	<div><div>Bridge type Concrete bridge Steel bridge Composite bridge Timber bridge</div><div>Structural components Railway track system Superstructure Substructure Foundation</div><div>Material and Energy Concrete, steel, painting, timber, rubber, aggregate, electricity, reinforcement, fuel</div></div>																																	
	Initial material and energy consumption																																	
Construction phase	Energy consumptions of construction machines Scaffoldings construction Traffic disturbances																																	
Maintenance and use phase	<div>Maintenance schedules with related traffic disturbances and transportation<table><tr><td>Structural</td><td>Maintenance activity</td><td>Ballast track</td><td>Fixed-slab track</td></tr><tr><td rowspan="7">Railway track</td><td>Rail grinding</td><td>1 year</td><td>1 year</td></tr><tr><td>Track direction</td><td>0.5 year</td><td>no repair</td></tr><tr><td>Rail replacement</td><td>25 years</td><td>25 years</td></tr><tr><td>Sleeper renewal</td><td>50 years</td><td>no repair</td></tr><tr><td>Fastener renewal</td><td>25 years</td><td>25 years</td></tr><tr><td>Rubber pad renewal</td><td>25 years</td><td>25 years</td></tr><tr><td>Ballast renewal</td><td>20 years</td><td>no repair</td></tr><tr><td rowspan="3">Superstructure</td><td>Repainting</td><td>30 years</td><td>30 years</td></tr><tr><td>Structural strengthening, patching and replacement</td><td>----</td><td>-----</td></tr></table></div>	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	----	-----
	Structural	Maintenance activity	Ballast track	Fixed-slab track																														
Railway track	Rail grinding	1 year	1 year																															
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	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	----	-----																															
	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

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
CML 2001, Eco-indicator 99, EDIP 97, EDIP 2003, EPS 2000, Impact 2002+, JEPIX, LIME, TRACI, IPCC

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

LCI data with the detailed manufacture procedures and known scopes, which are discussed in the earlier session, 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, eco-system and resource depletions. The recommendations of a broad set of specific life cycle stages for the railway bridge are described in below:

Material manufacture phase takes into account of the material manufacture and distributions from the raw material extraction until the ready-products to the construction site. This stage itself may compose a whole life cycle of material production, with the involvement of series activities from the 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 the final environmental performance largely relies on the selection of material types, which is a key factor to further affect 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 those mentioned process can be illustrated by a long list of LCI data. The LCI data is often provided by the commercial databases, with known study scope 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's 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.

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, thus would further affect the environmental performance. Through the literature survey, it has been found this phase is often omitted or roughly estimated in practical cases. The construction phase focuses on a wide range of operational systems, including the electricity consumption, the material transportation at site, the energy consumption from the construction machinery, the establishment of associated scaffoldings and the supporting systems. The type of construction machine varies from the earthwork cranes, forklift trucks, the excavators on site, soil compactor, excavator and the related transportations. However, the information of these operational machineries is usually unavailable from the contractor, or hard to estimate in the early project stage. For better promoting the sustainability development for bridges, the authority should require from the company to build a project-level based database system for construction information.

Maintenance and use phase is the longest life stage, which is responsible for a large proportion of environmental burdens due to replacing 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. (21th December, 2010. Personal contact by email, Trafikverket, Sweden). Just as in all maintenance tasks, there are several common repair tasks that apply to almost all bridges despite the materials used in construction; repairs can involve the 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, 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.

End of life phase is concentrated 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 the 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 where 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 found up to 88% (Fenton and Reston, 1998). The net benefits from 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 aggregated in road, while the aggregates can either be 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.

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

Structure	Structural element
Foundation	piles, embankment, abutment
Load bearing structure	slab, beam, truss, arch, cable, bracing, steel girder, frame, painting
Railway track	rails, sleepers, fixed slab track, ballast track, rail fasteners, rail pads
Bridge equipment	dehumidification machine, railing, parapet, bearing, joints
Earthwork	drainage, excavation, landfill

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 the high expectation to set new design criteria, optimize the design and assist the decision-making process among different design proposals.

1. Lack of uniform LCA guidelines and criteria is recognized 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 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 results comparison and product declaration should thus be handled carefully to ensure LCA analyses are performed 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 emphasizes on different emission inventory groups.’ However, different LCA results become incomparable when utilizing inconsistent data and methods. In practice, the principle for selecting the best probable LCIA method is the tendency to adopt the newest one 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 performed due to the limitation of the 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 manufacture factory is 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 the environmental profile of the structure is very case specific, that one cannot draw a general conclusion for a certain type of bridge without performing the LCA study. The transparent illustration of the operational procedure can improve the result reliability. For instance, Hammervold et al. (2009) compared three bridge designs, when using a unit surface area as a functional unit other than by the whole bridge; the concrete solution then became the most beneficial solution instead of the wooden bridge. Moreover, due to varying input parameters and the study scope, 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 don't 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 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 are highly recommended. It is thus proposed for the designer to utilize the structural component with suitable maintenance solutions, such as less small components of expansion joints, bearings or painting. For instance, Lounis and Daigle (2007), Keoleian (2005) pointed that high durable material benefit the environment due to the reduced maintenance, minimized 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 performs better environmental performance than the ballasted design.

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