Towards the Development of a Life-Cycle Assessment Framework for Bridge Management: A Literature Survey

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Abstract

The world is driven towards sustainable construction and there is increasing need for incorporating environmental considerations into asset management tools, models and frameworks. Structures such as bridges are subjected to deterioration due to increasingly demanding environmental conditions. In order to minimise deterioration and enable the selection of sustainable actions numerous maintenance and management approaches have been developed. However, there is limited consideration of environmental impact in Life-Cycle Assessment (LCA) during the decision making process. A life-cycle assessment can provide a detailed evaluation of environmental impacts of various maintenance options to allow the most sustainable method to be selected. The purpose of this study is to provide an overview of up-to-date literature on the implementation of LCA for bridge assessment. The review focuses on the LCA approach and methods adopted, life-cycle inventories considered for analysis, implemented framework developed and conclusions. Findings reveal that LCA for bridge infrastructure has concentrated on life cycle phases of the structure alone, without paying much attention to the available maintenance options. Literature has also revealed that most LCA studies have not clearly identified whether they have taken attributional or consequential approaches to LCA. Finally, considerations of benefits and barriers are also proposed for newly developed LCA frameworks before implementation.

Keywords

bridge, life cycle assessment, maintenance and sustainability

1. Introduction

The increased awareness of sustainable construction initiated in the early 1990's and companies are widely pursuing green products to achieve sustainable standards (Huang, 2007). Climate change and environmental impact are becoming important issues and include deterioration due to environmental impacts, depletion of resources and energy consumption (Thiebault *et al*., 2013).

The construction industry contributes heavily towards environmental impacts due to their increasing use of resources, pollutions and emissions (Azapagic, 1999). Presently, the construction industry has taken a holistic shift towards sustainable practices by providing guidance and initiatives in order to reduce environmental impact. Most of the guidance and initiatives are based on regulations to reduce harmful emissions and energy consumption.

Examples of sustainability initiatives for buildings are Energy Performance of Buildings Directive (EPBD) 2002, developed by European Union and later revised in 2010 (The European Union parliament, 2010), Building Research Establishment Environment Assessment Method (BREEAM)(BREAM, 2014) and Leadership in Energy and Environmental Design (LEED) that provides ratings for green buildings. Apart from buildings, initiatives have also been developed for highway infrastructures such as Best Value and Local Agenda 21.

Sustainability considers three main aspects, social, economic and environmental, known as the triple bottom line approach (Steele *et al.*, 2003) (See Figure 1). The environmental aspect of sustainable construction can be assessed through environmental tools such as Environmental Impact Assessment (EIA), Environmental Risk Assessment (RA), Substance Flow Assessment (SFA), System of Economic and Environmental Accounting (SEEA), Environmental Auditing (EA) and Flow Analysis (FA). Amongst all these assessment tools include LCA, which can quantify and evaluate the environmental performance of product and process (ISO 14040, 2006, Klöpffer, 2006). Apart from focusing on environmental considerations, LCA can include socio-economic considerations for construction.

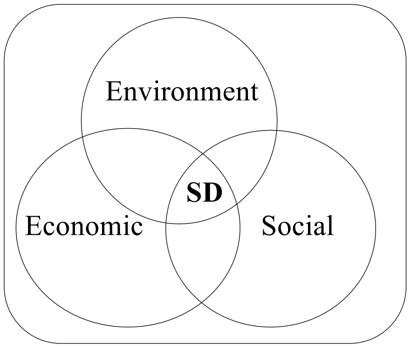

Figure 1: Triple bottom approach (SD) Sustainable development (Steele *et al.*, 2003)

LCA has widely gained grounds across various sectors within the construction industry and wide range of literature is available on methodologies and applications (Palmer *et al.*, 2011). The reason for the wide spread of LCA is its ability to capture inflow and outflow activities and their environmental impact during the life time of a structure or system (Horvath, 2009; Haung *et al.*, 2009; Crawford, 2011)

The current paper aims to provide an overview of the main approaches within LCA, that is attributional and consequential LCA and suggest ways of potential improvements.

2. Attributional and Consequential LCA

Weidema (2003) identified two categories of LCA goals. The first goal is to describe a product system and its environmental exchange and the second goal is to identify how environmental exchanges can be influenced by actions within the system. Curran *et al.* (2005) mentioned that the attributional and consequential approaches within LCA have evolved in an attempt to identify the relevant phases required within a given system.

According to Curran *et al*. (2005) attributional LCA is focused on the environmentally relevant physical inputs and output of a life cycle system and consequential LCA is aimed to describe how the environmental input and output will influence the decisions made. Therefore, the choice of LCA approach is dependent on individual choices (Consoli *et al.,* 1993, Guinée, 2002), which eventually influence the final framework. It can be observed that the first goal of LCA described by Weidema (2003) can be matched with Curran *et al*.'s (2005) attributional LCA and the second goal is in line with the consequential LCA respectively.

According to Hertwich (2005) attributional mode of LCA is a linear expression and represents the matrix of production, use and disposal process activities that reveals the product life cycle of a system. This suggests that in attributional modelling, the inflow and outflow of material energy must be followed by identifying the cradle-to-grave processes of the system under study (Pennington *et al*., 2004).

On the other hand, consequential LCA includes processes that are capable of making changes in the long- and short-run and can be used as a decision making tool (Curran *et al.,* 2005). Furthermore, consequential LCA has the ability to assess environmental consequences for decision made (Ekvall *et al*. 2005). Several authors in this field, for example Lundie *et al*. (2007) and Weidema (2003) have agreed that consequential LCA is more relevant for making decisions that may explain why LCA has been presented as a decision support tool. It may be possible to combine attributional and consequential LCA into one system, but as they represent different methodological approaches the system boundaries needs to be carefully identified and justified (Finnveden *et al*., 2009).

LCA framework for bridge management was developed by Steele *et al*. (2003). The framework was for a brick masonry arch bridge to investigate two strengthening options. Du (2012) also developed LCA framework for a railway bridge to aid new design criteria and decision making. LCA has mostly been used as a comparison tool and as a means of identifying the environmental performance of a particular bridge (Dequidt, 2012). However, there is need for a holistic LCA framework that can be integrated into present day bridge management strategies and practices.

The literature review is divided into two key areas. The first area considers the use of LCA to compare bridge type or materials, and the second area looks at the use of LCA for analysing a specific bridge in order to determine the life-cycle phase with most environmental impact.

3. LCA examples for comparing bridge elements

The section provides some examples of applying LCA for bridges

Example 1)

Widman (1998) applied LCA to compare two different structural forms (steel I-girder bridge with a concrete decking and steel box-girder) and identify the option with the best environmental performance. A cradle-to-grave analysis was considered that covered processes from raw material to demolition stage. LCA focused on the superstructure, substructure, railings and pavement but excluded joints, bearings, ground reinforcement and piling. Impact per square meter lane was considered as a unit to enable easy comparison. Inventory data was obtained from three different manufacturers' data base (Swedish, Norwegian and Finnish). Inventory data collected from the Swedish data base was subjected to three different method of analysis: Environmental Priority Strategies in Product Design (EPS), Environmental Theme Method and Ecoscarcity Method.

The LCA results indicated that CO_2, SO_2 and NO_x were the main emissions to air, however CO_2 and NO_x have the greatest environmental impact due to transportation of materials. Traffic during the use of the bridge also accounts for great CO_2 and NO_2 emission, however emission during maintenance is negligible. The Ecoscarcity results indicated that environmental damage already incurred during the combustion of fossil fuel, that led to Widman's conclusions that using micro alloyed steel instead of steel with higher percentage of alloy will reduce the environmental impact of bridges (although it was not stated if this was specifically for maintenance phase alone or it included the construction and end of life scenarios).

Example 2)
Horvath and Hendrickson (1998) compared LCI results of a steel girder bridge and a steel-reinforced concrete bridge. Again, the purpose of this study was to identify the bridge with lower environmental impacts. LCA was carried out for the manufacturing phase, use of the structure, maintenance phase and the End-of-Life (EOL) phase using Economic Input-Output Life Cycle Assessment. From the phases considered it can be assumed that a cradle-to-grave approach was taken. In the analysis, consumption of electricity, fuels, chemicals and minerals were considered for the input data, while chemical discharge (to air, water, land, and underground wells), hazardous emissions to air where considered for the output.

LCI analysis revealed that a steel-reinforced concrete bridge had better environmental performance considering the whole life compared to a steel girder bridge and that the end life of steel girder is more sustainable compared to concrete for recycling options. Horvath and Hendrickson (1998) concluded that there was insufficient data available for data analysis that probably influenced the result.

Example 3)
Martin (2004) compared a pre-stressed concrete bridge deck with a steel-concrete composite bridge deck to evaluate the one with the lowest environmental impact. During the cradle-to-grave analysis it was indicated that the pre-stressed concrete deck used 39% less energy than the steel-concrete composite and also generated 17% less greenhouse gases (GHG). For recycling the pre-stressed concrete also consumed less energy, however the steel-concrete composite resulted to 30% less emission of GHG.

Further examples of the application of LCA for bridges are listed in table 1

Table 1: LCA examples for comparing bridge elements

Authors	**Bridges Compared**	**Phases considered**	**Components Considered**	**Impact categories/ Indicators**	**Results (Environmental performance)**
Steele *et al*. (2002)	Masonry arch bridges: different design and construction materials	- Construction - Maintenance	Strengthening technique: - Concrete saddle - Anchor installation	-Vehicle disruption - Construction of brick bridge - Construction of reinforced saddle - Anchoring strengthening SimaPro indicators.	- Construction phase of the bridge had greater environmental impact than the strengthening methods - Construction of concrete saddle had greater environmental impact.
Itoh and kitagawa (2003)	Girder Bridge: - pre -tensioned concrete, - pre-tensioned concrete box - steel non-composite box	- Construction	-Super structure - Sub structure	- CO_2 - Energy consumption	Environmental burden was higher: - at the manufacturing stage for all the options. - higher for steel girder
Itoh and kitagawa (2003	- Convention design - minimized girder bridge	- Construction, maintenance - replacement	- Super structure - Sub structure	- CO_2 - Energy consumption	- Conventional design yielded more CO_2 than the minimized girder

Keoleian *et al.* (2005)	Reinforced concrete deck: - conventional steel expansion joints - Link slab concrete design engineered with cementations composite (ECC).	- Material production, - construction, - use - end of life	- Deck	- Energy consumption - Global warming	- ECC yielded more energy saving potentials and reduced environmental pollutant emissions.
Collings (2006)	3 bridge form: - Cantilever, - Cable stayed - Steel arch Bridge type - orthotropic steel girder - concrete girder - steel-concrete composite girder	- Construction - maintenance	- Super structure	- Energy use - CO_2 emission	- Concrete girder consumed less energy and yielded lesser CO_2 emissions
Gervásio and da Silva (2008)	Two design alternatives: - I-girder steel-composite - concrete-concrete twin U-girder.	- Construction	- Super-structure excluding the piers	- Emissions - CO_2, SO_2, NO_X, VOC, CO, CH_4 and particulates Impact categories (Water intake, smog, Global warming, Eutrophication, air pollutants and acidification)	- Steel-concrete composite had better environmental performance than the concrete-concrete alternatives
Lounis and Diagle (2007)	- Reinforced concrete deck – designed for normal concrete - - High performance concrete (HPC) added with supplementary cementing materials (SCMs) in the mixture	- All life cycle phases from material extraction to material disposal	- Deck	- CO_2	- CO_2 emissions were three times higher than the HPC alternatives. Replacing the normal concrete during maintenance explained the variations.
Brattebø *et al.* (2009)	– Steel box girder – Wooden arch – Concrete box girder	- Material extraction, - Manufacturing, - Construction, - Use - End-of-life phase	- Super structure - Preparation of the foundation	- Depletion of abiotic resources, - acidification - eutrophication, - climate change - ozone layer depletion - photo-oxidant creation	- Concrete box girder had the best environmental performance.
Thiebault (2010)	Railway steel-concrete bridge: - Ballasted - Fixed concrete	- Material production - Construction - Use - End-of-Life	- Super structure	- Abiotic depletion - Global warming - Human toxicity - Photo-oxidant - Acidification - Eutrophication	- Fixed concrete track imposed 77% less environmental impact

3.1 LCA examples for specific bridge

Example 1
Bouhaya *et al*. (2009) used a simplified LCA to investigate a road bridge made of wood and Ultra-High Performance Concrete (UHPC) slab. All the life cycle stages were considered for the analysis, from raw material extraction to the end-of-life. However elements such as barriers, sidewalks, pavement and proofing material were excluded from the analysis. Foundations were also not accounted for, but energy releases and greenhouse emission over a 100-year service life were considered.

Due to lack of available data several assumptions were made for the UHPC. For instance UHPC was assumed to be maintenance free over the 100 year service life and the wooden component was assumed to be replaced on an economic balance bridge maintenance scale. CO_2 release was based on the overall component of the bridge. Three end-of-life scenarios were considered here. Firstly the timber was used as landfill, secondly it was burnt for heating and thirdly it was recycled. Result revealed that most energy required was during the manufacturing phase. For the analysis only the released energy and greenhouse gases were accounted for, whereas Horvath (2009) emphasized that a good LCA analysis should consider a wide range of pollutants to air, water and waste rather than concentrating on the emissions from greenhouse gases alone.

Example 2
Dequidt (2012) investigated a Norwegian bridge (post-tensioned concrete-girder deck of 165m span and 670m length) using LCA methodologies. Five life cycle phases were considered: material production, construction, operation, maintenance and repair and end of life. Material production phase was divided into superstructure, substructure and subsidiary elements. The super-structure included concrete deck box-girder and non-structural elements, sub-structure included abutments, columns, caisson, foundation and piles.

At the construction phase transportation to site, energy consumption on the construction site and waste management was considered. For the operation phase all aspects of the bridge were considered, such as traffic-related emission, traffic growth rate and supply for public lightning. For the maintenance and repair phase three main processes were considered simple visual inspection (every year), main inspection (every 5 years) and asphalt course renewal (every 3 years). Finally the end of life phase considered reinforced concrete, asphalt, gravel, railings and parapets. For this study only global warming category (GWP) was accounted for, while other indicators such as ozone depletion, eutrophication etc. was not considered. The result indicated that the superstructure, production phase, maintenance phase, concrete, steel and asphalt were the major contributors to environmental impact.

The above examples indicate that LCA has been largely used to compare the environmental impact of different bridge options but has not been greatly explored for comparing different maintenance options for bridges. Limited use of LCA for maintenance options may have originated from the assumption that most impact is accumulated during the construction rather than the maintenance phase. However, investigating LCA for various maintenance options will further assist decision makers regarding the selection of sustainable maintenance method. Therefore a case is presented to conduct a research on the implementation of LCA for various bridge maintenance options.

Finally, it was observed that most of the reviewed papers have not attributed their approach to either attributional or consequential LCA. It follows that the attributional and consequential theories have not been fully absorbed into LCA investigations. Further research towards investigating the benefits and barriers of two approaches is also needed.

4. Concluding remarks

A state-of-the art literature has now been established. It has been argued that LCA can be used as a comparison tool and also as a means of analyzing individual bridges to asses and demonstrate their environmental performance. A line of argument which promotes the need for maintenance options to be assessed using LCA has been presented. Research to address this gap is currently being undertaken. Further research needs to be conducted to address the benefits and barriers of pursuing such an LCA approach.

5. References

Azapagic, A. (1999) "Life cycle assessment and its application to process selection, design and optimisation": Review article. *Journal of Chemical Engineering*. 73 (1), pp. 1-21.

Brattebø, H., Hammervold, J. and Reenaas, M. (2009*) Environmental Effects – Life Cycle Assessment of bridges*. Sub project. Norwegian University of science and technology. Norway

BREEAM (2014) *The world's leading design and assessment for sustainable buildings*. Available [online] at: http://www.breeam.org/about.jsp?id=66 (Accessed 12 January, 2015)

Collings, D. (2006) An environmental comparison of bridge forms. *Proceedings of the Institute of Civil Engineers*. 159 (BE4), pp. 163-168

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A. (1993) *Code of Practice: Guidelines for life-cycle assessment*. Pensacola, USA: SETAC

Crawford, H. (2011) *Life Cycle Assessment in the built Environment*. 1st Edition. London and Newyork: Spon Press

Curran, M., Mann, M., Norris, G. (2005). "The international workshop on electricity data for life cycle inventories". *Journal of Cleaner Product*. 13 (8), pp. 853–862.

Dequidt, T. (2012) *Life Cycle Assessment of a Norwegian Bridge*. MSc. Norwegian University of Science and Technology. Norway

Du, G. (2012) *Towards Sustainability Construction: Life Cycle Assessment of Railway Bridges*. PhD. Royal Institute of Technology, Sweden.

Ekvall, T., Tillman, A., Molander, S. (2005) "Normative ethics and methodology for life cycle assessment". *Journal of Cleaner Product*. 13 (14), pp. 1225–1234.

Finnveden, G., Hauschild, M., Ekvall, T., Guinee, J., Heijungd, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S. (2009) "Recent developments in life cycle assessment". *Journal of Environmental Management.* 91 (1), pp. 1-21

Gervásio, H. and Simões da Silva, L. (2008) "Comparative life-cycle analysis of steel-concrete composite bridges". *Journal of Structure and Infrastructure Engineering.* 4 (4), pp. 251-269.

Guinée, J. (2002) "Handbook on life cycle assessment operational guide to the ISO standards". *The International Journal of Life Cycle Assessment.* 7 (5), pp. 311-313.

Hauschild, M. Z. (2005) "Assessing environmental impacts in a life-cycle perspective". *Journal of Environmental Science Technology*. 39 (4), pp. 81a-8a

Huang, Y. (2007) *Life Cycle Assessment of use of Recycled Materials in Asphalt Pavement*. PhD, School of Civil Engineering and Geosciences Newcastle University.

Hertwich, E. (2005). Life cycle approaches to sustainable consumption: a critical review. *Journal of Environmental Science Technology*. 39 (1), pp. 4673–4684

Horvath, A and Hendrickson, C. (1998) "Steel versus steel-reinforced concrete bridges: Environmental assessment". *Journal of infrastructure system*. 4 (3), pp. 111-117

Horvath, A. (2009) Principles of using life-cycle assessment in bridge analysis. *Proceedings of US-Japan Workshop Life Cycle Assessment of Sustainable Infrastructure Materials.* Sapporo, Japan, October 21-22, 2009

International Standard 14040 (2006*) Environmental management* – *life cycle assessment* – *principles and framework.* 2nd Edition. Geneva: International Organisation for Standardization (ISO).

Itoh, Y and Kitagawa, T. (2003) "Using CO2 emission quantities in bridge lifecycle analysis". *Journal of Engineering Structures*. 25 (5), pp. 565-577.

Keoleian, G., Kendall, A., Dettling, J., Smith, V., Chandler, R., Lepech, M., and Li, V. (2005) "Life cycle modelling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints". *Journal of Infrastructure Systems*. 11 (1), pp. 51-60

Klöpffer, W. (2006) "The role of SETAC in the development of LCA". *International Journal of Life Cycle Assessment*. 11 (1) pp. 116 – 22

Lounis, Z. and Daigle, L. (2007) Environmental benefits of life cycle design of concrete bridges. *Proceedings of the 3rd International Conference on Life Cycle Management, Zurich, Switzerland.* August, 27-29, 2007*,* pp. 1-6.

Lundie, S., Huijbregts, M.A., Rowley, H., Mohr, N., Feitz, A. (2007). "Australian characterisation factors and normalisation figures for human toxicity and ecotoxicity". *Journal of Cleaner Product*. 15 (1), pp. 819–832

Martin, A.J. (2004) "Concrete bridges in sustainable development". *Proceedings of the Institute of Civil Engineers.* 157 (4), pp. 219-230

Ortiz, O., Castells, F and Sonnemann, G. (2009) "Sustainability in the construction industry: A review of recent developments based on LCA". *Journal of Construction and Building Materials*. 23 (1), pp. 28-39

Palmer, P., Puig, R., Bala, A., Baquero, G., Riba, J and Raugei, M. (2011) "From Life Cycle Assessment to Life Cycle Management: A case study on Industrial Waste Management Policy Making". *Journal of Industrial Ecology*. 15 (3), pp. 458-475

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T.,Schmidt, W., Suh, S., Weidema, B.P., Pennington, D. (2004) "Life cycle assessment – Part 1: Framework, goal & scope definition, inventory analysis, and applications". *International journal of environment*. 30 (1), pp. 701–720.

Steele, K., Cole. G., Parke. G., Clarke. B and Harding, J. (2003) Highway bridges and environment – sustainable perspective. *Proceedings of Institute of Civil Engineers*. 156 (4), pp. 176-182.

Steele, K., Cole. G., Parke. G., Clarke. B and Harding, J. (2002) Application of Life Cycle Assessment Technique in the investigation of Brick Arch Highway. *Proceedings of the 2002 conference for the Engineering Doctorate in Environmental Technology*. University of Surrey.

The European Union parliament (2010) *Directive 2010/31/EU of the European parliament and the council*.Available[online]at:http://www.eceee.org/policy-areas/buildings/EPBD_Recast/EPBD_recast_19May2010.pdf (Accessed 10 January, 2015)

Thiebault, V. (2010) *Design of Railway Bridges considering LCA*. MSc, Royal Institute of Technology, Sweden.

Thiebault, V., Du, G. and Karoumi, R. (2013) "Design of railway bridges considering life-cycle assessmen"t. *Proceedings of Institute of Civil Engineering*. 166 (BE4), pp. 240-251.

Weidema, B., Hischier, R., Althaus, J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Jungbluth, Nemecek, T., Primas, A and Wernet, G. (2009). *Code of Practice*. Ecoinvent report No.2, Swiss Centre for Life Cycle Inventories, St. Gallen

Widman, J.(1998) "Environmental impact assessment of steel bridges". *Journal of Constructional Steel Research*. 46 (1), pp. 291-293