Third International Conference on  Sustainable Construction Materials and Technologies   http://www.claisse.info/Proceedings.htm

# Environmental life cycle assessment comparison between two bridge types: reinforced concrete bridge and steel composite bridge

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## ABSTRACT

The concept of sustainable construction has attracted an increased attention. Bridge infrastructures and their belonged construction activities consume considerable material and energy, which is responsible for large environmental burdens. However, the environmental assessment of bridges has not been integrated into the decision-making process. This paper presents a systematic LCA method for quantifying the environmental impacts for bridges. The comparison study is performed between a reinforced concrete bridge and a steel bridge as an alternative design, with several key maintenance and EOL scenarios outlined. LCA study is performed with the ReCiPe methodology with life cycle inventories data from public database. Five selected mid-point level impact categories and the energy consumption are presented. The result shows that the steel bridge has a better environmental performance due to the recycling strategy, while the initial material manufacture is the most dominant phase that contributes large environmental impact in both design solutions.

**Keywords.** LCA, Bridge, Sustainable construction, Life Cycle Assessment, Global warming

## INTRODUCTION

Due to the increased demand of the transportation network in the past decades, the growth of the infrastructure quantities remains considerable in Sweden. As the fundamental structures in the transportation network, the bridge infrastructure not only consumes numerous natural resources and energy but also have long-term life span, which results into significant concerns of the environmental impact. However, the current decision making process is still mainly focused on the technique, safety and economic perspectives, that the environmental assessment is not yet integrated. From the environmental perspective, the decisions made today may have a long-term effect for the whole life cycle of bridge. For mitigating the environmental impacts from the bridge infrastructures, the administration and stakeholder initiate the efforts on integrating the environmental assessment into the current project management.

One comprehensive approach used for quantifying the environmental impact and energy consumption of bridges is the life cycle assessment (LCA). LCA is deemed as a versatile tool to investigate the environmental aspect of a product, a service, a process or an activity by identifying and quantifying related input and output flows utilized by the system and its delivered functional output in a life cycle perspective (Baumann et al., 2003). The implementation of LCA into bridges is under expectations to set a new design criterion, to optimize the structural design and to assist the decision-making among different design proposals.

The Swedish bridge infrastructures take large portion in the construction sector, until 2012, around 16701 road bridges and 4126 railway bridges were registered in the Swedish bridge and tunnel administration system. The selection of material and bridge types is a vital task in the bridge project, which may have a long-term effect for the whole life cycle environmental performance. Most bridges are built by the reinforced concrete and steel composite material. Steel as the dominant construction materials in bridges, it initially involves a higher value of embodied energy and emissions than the concrete. However, the 100% recyclable property of the steel material has further led the high competition from the concrete.

Based on these considerations, this paper presents a generalized LCA framework for bridges, which aims at assisting the decision-maker to select the optimal alternative in the early stage. Furthermore, a comparative LCA study is carried out on two design proposals for the new planed Skurup highway bridges in Sweden: a reinforced concrete bridge and a steel I-girder composite bridge. A comprehensive LCA study is performed by the ReCiPe (H) methodology (Goedkoop et al., 2009), with different life cycle inventory (LCI) data collected from a various public database sources. The cumulative energy demand (CED) and five selected mid-point level impact criteria are compared between two design proposals: climate change (GWP), ozone depletion (ODP), human toxicity (HP), photochemical oxidant formation (POFP), particulate matter formation (PMF). The result may provide the reference knowledge to the authority regarding the selection of bridge types in the early design stage.

## LIFE CYCLE ASSESSMENT METHODOLOGY

Life cycle assessment (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). The potential environmental takes account of resource depletion, human health, and ecological health (ISO14040). However, the current LCA series of ISO standards were developed focusing on the guidance purpose rather than the practical specifications (Fava J. A. 2011). There are four steps involved in the LCA framework, which is illustrated in below:

**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 description of study scope, the purpose and assumption should be addressed clearly, as well as the included life span phases, relevant future scenarios and product components.

**Life cycle inventory phase.** The life cycle inventory (LCI) takes account of the inputs and outputs relates 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 are collected from various sources including manufacture factory, government, commercial databases, and scientific journals.

**Life Cycle Impact Assessment (LCIA).** It 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 normalization, grouping and weighting (ISO 14044, 2006).

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

## CASE STUDY OF THE NEW SKURU BRIDGE

There are currently two Old Skuru Bridges located in the Nacka commune outside Stockholm, which served as the only road link between Stockholm and the Eastern Värmdö municipality. The traffic volume is predicted to be increased from current 57,000 vehicles per day to 85,000 vehicles per day in 2030. In order to keep the infrastructure development with the increased traffic expansion, the Swedish Road Administration (Trafikverket) proposed to build a New Skuru Bridge in year 2013 beside the two old Skuru bridges. The new bridge will be of high artistic and architectural quality and work with the existing bridge, surrounding cultural and natural landscape. In this paper, the LCA framework for bridges is implemented on two design alternatives of the Skurup Bridge: a steel I-girder bridge and a reinforced concrete beam bridge. Both designs are proposed as a conceptual alternative for the New Skuru Bridge, which is 373 m length, 29.5 m width and 30 m height. The cross-section of both proposals is presented in Figure 1. The conceptual designs are modified from the existing built bridge in Sweden, with the dimension parameter listed in Table 1.

**The Reinforced Concrete Bridge Alternative.** The concrete alternative consists of two parallel beam bridges of 13.5 m width each, separated by a 2.0 m distance in between. 44 tons aluminum parapets are installed on the bridge deck. The superstructure is pre-fabricated with the pre-stressed tendons aligned through the whole bridge. The whole cross section is reinforced concrete slab which is constant with 1.7 m thickness cast on site. The substructure is supported by 7 circular reinforced concrete columns with 1.4 m diameter.

**The Steel I-girder Bridge Alternative.** This design consists of a reinforced concrete deck of 0.265 m thickness and two steel-I girder beams as the main load bearing component in the superstructure. The whole superstructure is loaded on eight squared reinforced concrete columns. Served as the main loading bearing components, the steel I girder section has a varied height between 1.13-2.02 m along the bridge, which is galvanized and painted with epoxy to prevent corrosion. The steel bracing severed to stabilizing against the lateral buckling is placed between the steel I girder beams in every 4.5 meters.

**Table 1. The dimension specification of two design alternatives**

| Bridge specifications | unit | Reinforced concrete bridge | Steel I-girder bridge |
|---|---|---|---|
| Total bridge length | m | 373 | 373 |
| Total bridge width | m | 29.5 | 29.5 |
| Total bridge area | $m^2$ | 10257 | 11004 |
| Steel painting area | $m^2$ | -- | 2585 |
| Paved area | $m^2$ | 9231 | 9903 |
| Bearings number | set | 12 | 20 |
| Parapets length | m | 1564 | 782 |
| Edge beam length | m | 1492 | 746 |

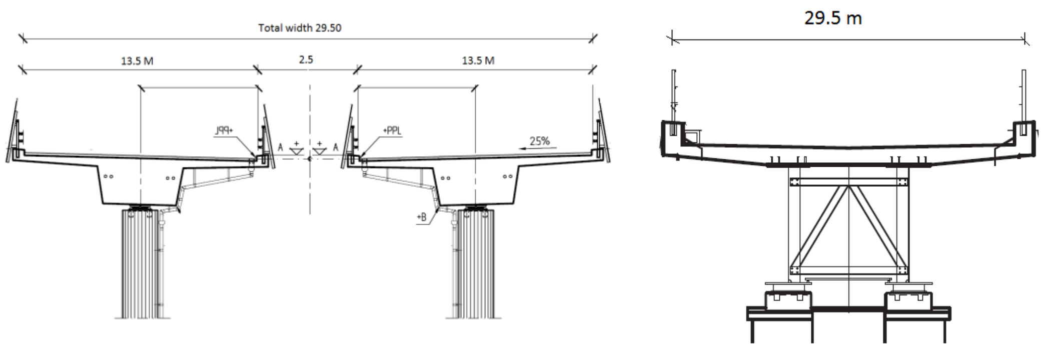



**Figure 1. The design proposal of reinforced concrete bridge and steel composite bridge**

**Goal and scope** the comparative LCA study is intended to analyse the environmental performance for the whole life cycle of two design alternatives. The study covers all the structural components of the bridge, including superstructure of reinforced concrete slab, structural steel section with bracing, the substructure of columns, abutments and the foundation piles. The functional unit is chosen as the whole bridge with the same span length and width, serving the same annual traffic capacity, with the Eurocode of 100 years life span. The comparison is performed on the basis of this chosen functional unit from 'cradle' to the 'grave', through the material manufacture phase, construction phase, maintenance phase to the EOL phase.

**Life Cycle Inventory Analysis.** The material quantities necessary for modelling the material manufacture phase are quantified based on the design drawings with the related LCI data sources, see Table 2. The implemented LCI data are retrieved from the public database with aggregated value, by referring to the average European conditions, including the source of Ecoinvent v2.2 database, ELCD and world steel association, which fully covers the necessity upstream processes, various raw material and energy utilized in each sub-processing. The related air emission flows, water and solid releases are modelled from the material of steel, reinforcement, wired rod, stainless steel, structural steel, painting, aluminium and the concrete. The material transportation are analysed by the truck lorry 3.5-16 t full fleet and ship freight, with the assumed distances from the potential suppliers to the construction site.

**Life Cycle Assessment of the New Skuru Bridge.** Four life stages are fully analysed in the life cycle assessment model of the New Skuru Bridge, from the material manufacture phase,

**Table 2. The input quantities at the initial material manufacture stage**

| Structural items | Unit | Proposal 1 | Proposal 2 | Type of material | LCI Database | Transportation distance |
|---|---|---|---|---|---|---|
| Concrete | $m^3$ | 14191 | 10863 | Normal concrete & Concrete sole plate and foundation | Ecoinvent | 60 km by truck |
| Reinforcement | ton | 2563 | 1020 | Reinforcing steel, at plant | World steel association and Ecoinvent | 150 km by truck |
| Structural steel | ton | --- | 1055 | Low alloyed steel, at plant | World steel association and Ecoinvent | 400 km by ferry + 100 km by truck |
| Aluminium parapets | kg | 43948 | 21974 | Production mix of Aluminium at plant | Ecoinvent | 100 km by truck |
| Bearing | kg | 1236 | 2060 | Stainless steel hot rolled coil | ELCD | ---- |
| Painting | $m^2$ | --- | 2585 | Zinc coating | Ecoinvent | ---- |

**Table 3. The considered structural elements for the New Skuru Bridge**

| Structure | Structural element |
|---|---|
| Foundation | Abutment, columns, piles |
| Load bearing | Beam slab, bracing, steel girder |
| Bridge equipment | Bearing, painting, parapets |

construction phase and maintenance phase till the EOL. The selected environmental impact categories are calculated from each bridge structure component from the bridge deck in the superstructure to the foundation columns in the substructure. The methodology of LCA for bridges is followed by the framework guide proposed in Du and Karoumi (2012b) with the developed Matlab-based tool:

**The Material Manufacture Phase.** It takes account of the raw material extraction and distribution processes of a series of activities, based on the information retrieved from the LCI databases. Table 3 displays the considered structural element of the bridge in this case study. The direct and indirect energy and emissions from this phase are quantified with the inventory data. Instead of counting the environmental benefit of the recycling process in the EOL, it is counted in the material manufacture phase that the steel contains average 37% secondary steel scrap.

**The Construction Phase.** This phase mainly focuses on the energy consumption from the construction machine and the material transportation vehicles. The difficulty in this phase has been realized as very little information is available, since the energy consumption from the construction machines are often not reported from the historical data. There are no history data for the fuel consumption from the construction machines such as dumper, soil compactor, and excavator. Besides, the energy consumption may largely depend on the factors of the construction techniques, the bridge type, size and the material quantities. Due to lack of the information, in this study, the specific energy consumption from the machinery operating is assumed to be approximately 0.1 L diesel burned in a building machine per $m^3$ mass moved (Hammervold J. et. al, 2011). The fuel consumption from the material transportation is modelled by truck and ship lorry from the potential supplier to the site.

**The Maintenance Phase**. It contains the regular maintenance of structural elements, including replace the bearing, edge beam and parapet and repainting the steel section. Thus the machinery operation, related traffic disturbances and extra material consumption in this stage will result into extra material and energy consumptions. Table 4 listed the realistic maintenance activities considered in this study, that the bridge bearings are replaced twice, steel sections are repainted three times, edge beam is replaced 3 times and the parapets is replaced once in the 100 years life span. However, the realistic maintenance intervals are largely influenced by the designed service life, traffic load, periodic inspection and the budget plan (Du and Karoumi, 2012a). The related energy consumption and extra material consumption are calculated based on Table 4.

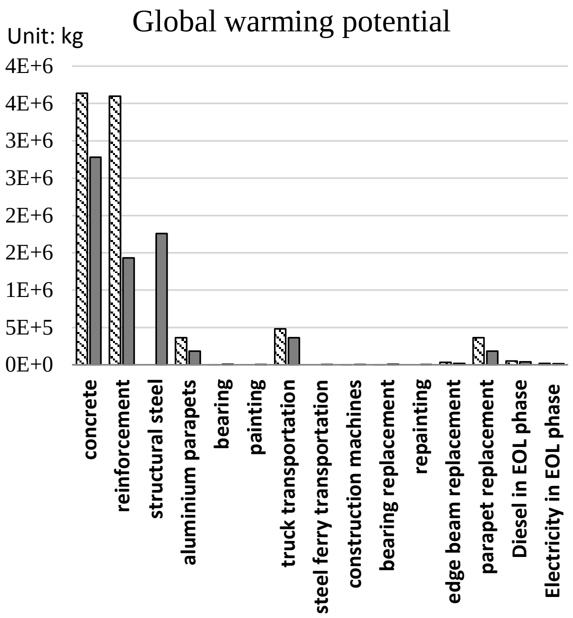
**The EOL Phase.** Construction and demolition waste account for a large percentage of total solid waste. Different demolish strategies, material reuse or recycling scenarios are critical issues involved in the EOL stage. In this case study, the EOL phase takes account of the steel recycling and concrete crushing scenarios. The avoided burden from steel recycling is accounted in the initial material manufacture phase by a mix of 37% secondary steel. The concrete are assumed to be crushed into aggregates for roads sub-base filling material. The consumption of 16.99 MJ Diesel and 21.19 MJ electricity is estimated for crushing 1 ton of aggregates from the concrete (Stripple 2001).

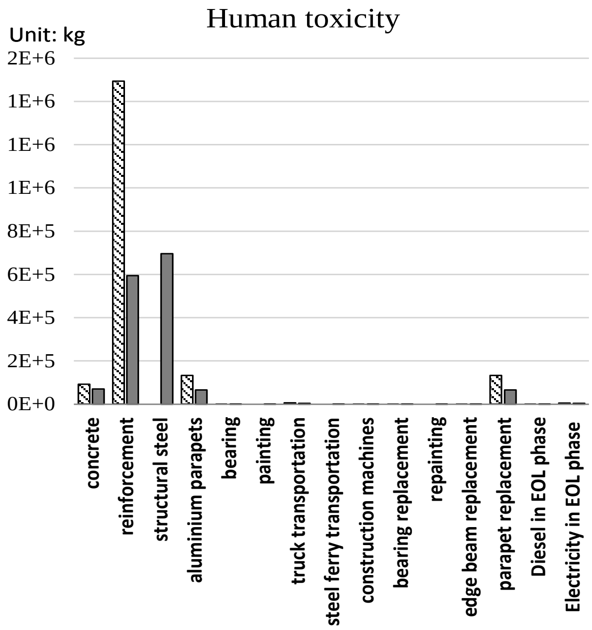
**Table 4. The maintenance schedules through the whole life cycle**

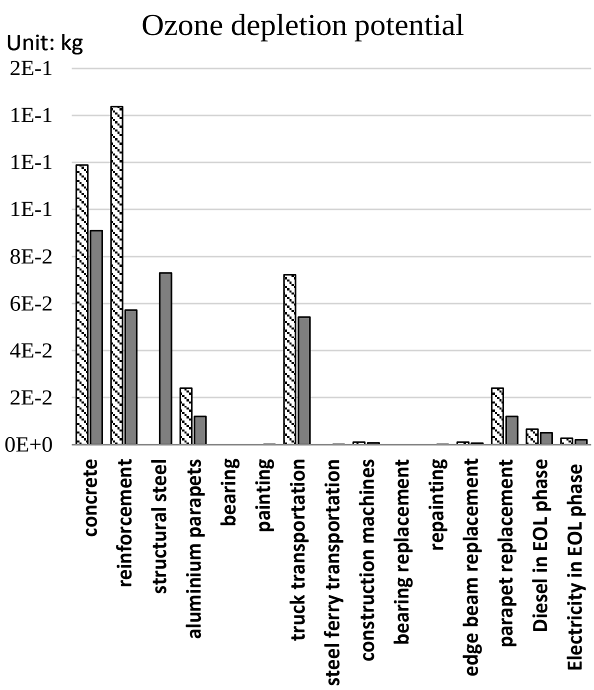
| Maintenance activities | Unit | Maintenance interval [years] | Proposal 1 | Proposal 2 |
|---|---|---|---|---|
| Bearing replacement | kg | 40 | 1236 | 2060 |
| Repainting of the steel | $m^2$ | 30 | --- | 2585 |
| Edge beam replacement | $m^3$ | 25 | 134 | 67 |
| Parapet replacement | kg | 50 | 43948 | 21974 |

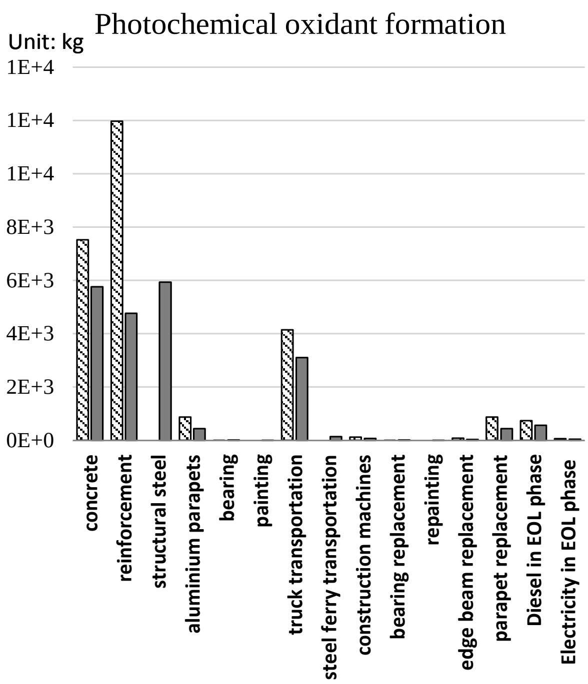
## RESULT

In the case study of the New Skuru Bridge, the environmental comparison is carried out from ‘cradle to grave’ between two design alternatives: a pre-stressed concrete design and a steel composite design. The analysis is performed based on the implementation of a comprehensive life cycle impact assessment method ReCiPe and a wide range of LCI databases including Ecoinvent v2.1, world steel association and Stripple (2001). In particular, a full list of inventory results are transformed into category indicators by the use of characterization factors, with investigating five selected impact categories oriented at a



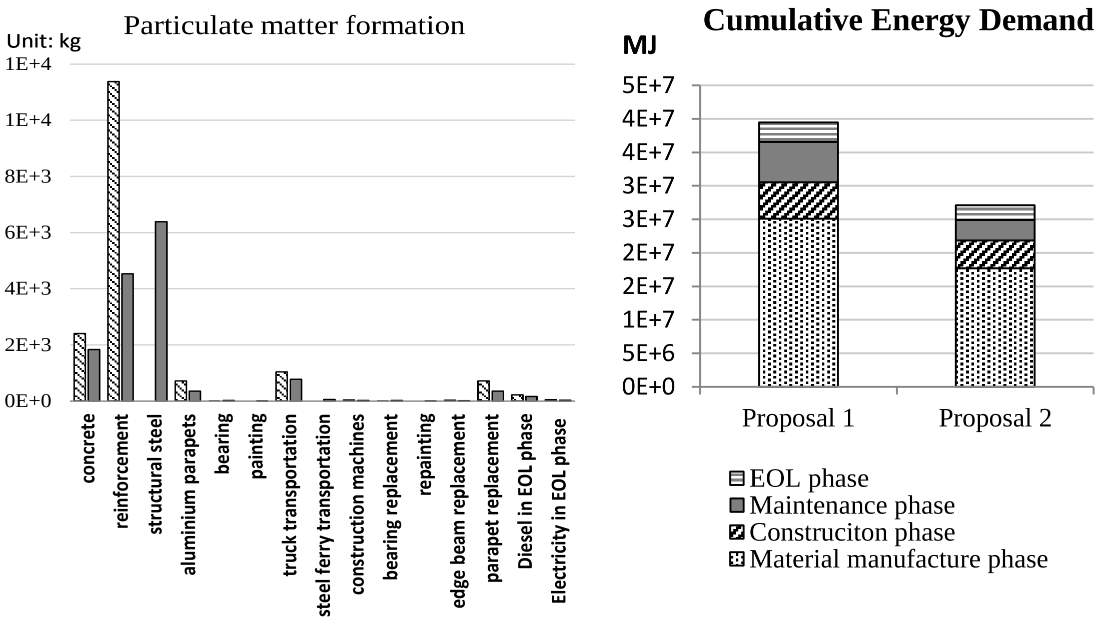



**Figure 2. Environmental impact according to structural components and activity scenarios**

'mid-point' level, listed as: Global warming potential (kg CO2 eq.), Ozone depletion potential (kg CFC-11 eq.), Human toxicity potential (kg 14-DCB eq.), photochemical oxidant formation potential (kg NMVOC eq.), Particulate matter formation potential (kg $PM_{10}$ eq.) (Goedkoop et. al., 2009). Besides, the cumulative energy demand (CED) is also presented.

According to Laurent et al., (2012), the global warming potential cannot fully represent the environmental profile of the bridge. Thus, for obtaining the full picture of the environmental performance, this paper chose five environmental impact categories and energy consumption; Figure 2 depicts the characterized results of environmental impact allocation due to each structural component and scenarios through the whole life cycle. The result reveals that the initial material manufacture is the largest contributor in each design alternative. The steel composite proposal presents the preferable environmental performance based on the selected impact categories, which is respectively 45% less in CED, 21% less in GWP, 19% less in ODP, 22% less in HP, 19% less in POFP and 12% less in PMF, when comparing with the concrete bridge solution. The main reason is due to the less material in the steel composite bridge, with the accounted avoided environmental burden from 37% secondary steel, even though the virgin steel manufacturing has higher embodied environmental burdens than the normal concrete. In both design solutions, the reinforcement and concrete as the main structure material dominates up to 91% environmental impact in each category, followed by the material transportation up to 18% and the maintenance activities up to 8%. Besides, the environmental burden from the construction phase, the small structural work of bearing, painting and construction can be negligible. The CED consumption in each design proposal is largely dominated by the initial material manufacture phase, which takes account of up to 65%; while the construction phase, maintenance and use phase, EOL phase represents up to 15%, 15% and 8% respectively between two design proposals.

## CONCLUSIONS

Environmental concern has increased in the infrastructure industry, which is responsible for enormous material consumption and considerable environmental impact. Although bridges play an important role in the construction sector, their environmental impact are not yet considered in the decision making process. The research and literatures in this field is very scares. With the intention to quantify the environmental impact of the bridges based on the comprehensive LCA methods. This paper presented a comparative LCA study between two alternative designs: the reinforced concrete bridge and the steel-composite bridge. The results revealed that the steel composite proposal showed the advantages in all the selected impact categories. The study has improved the practice and implementation of the LCA methodology in the bridge industry and provides a reference for the authorities.

The structural design affects the life cycle scenarios and material quantities, thus further influencing the final environmental impact. For instance, the steel enables the bridge to be designed with slender and thinner deck, plus the full recycling properties, the steel bridge option shows better environmental profile in several categories than the concrete deign. Besides, the material manufacture phase has been identified as the most decisive phase through the life cycle in both designs. While the waste treatment scenarios in the EOL stage shows critical advantage in reducing the raw material consumption and the generation of the related environmental impacts. Regarding the environmental performance in general, the contribution from various structural components and life cycle scenarios are different in the targeted environmental impact category.

Through the study, the lack of realistic LCI data is identified as one main obstacle hindering LCA implementation. The development of a consistent and local database remains as a shot term goal to achieve for LCA practitioners and the authority. That only the public LCI database was implemented. Besides, the realistic construction and maintenance scenarios were performed based on the assumption which may cause varied results. Although the study has increased the knowledge of assessing the environmental burden for the bridge projects, the result cannot be used directly in other cases and one should avoid drawing a generalized conclusion based on one case study, because of a various uncertainties being involved.

A number of LCIA methods have been developed by different research institutes with the emphasis on several specific impact categories, including Impact 2002+, CML, EPS2000, etc. The analysis in this paper was performed based on the ReCiPe 2008 method; however, the results would be varied by other methods, which require the efforts for the establishment of localized impact factors.

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