Life Cycle Assessment on modern timber bridges

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Abstract

Demands of sustainability and environmentally friendly structures have been rising rapidly in recent years, especially in Nordic countries where timber has been strongly promoted in the construction sector. Due to this tendency, a reliable assessment of the environmental performance of timber bridges through their life cycles is needed. Life Cycle Assessment (LCA) is chosen as the common approach to conduct the assessment, but so far, the implementation of LCA on timber bridges is rather limited. To have an overview of the environmental performance of timber bridges, this paper surveys literature about LCA implementations on modern timber bridges and on bridges made of other materials as reference. Variances between the investigated LCA implementations and their influences are documented and discussed, including the specification of the goal, the applied Life Cycle Impact Assessment methods, and the interpretation. Common conclusions from the literature are classified, e.g. the material production stage results in the largest share of environmental impact or the effect of transport disruption during bridge maintenance should be considered. The survey reveals that there is lack of uniformly agreed criteria on LCA for timber bridges. The paper concludes critical issues, challenges, and possible improvement for the future LCA implementations on timber bridges.

Keywords: LCA; timber bridges, CO_2 emissions, LCIA

1. Introduction

Climate change has been one of the most tremendous challenges for human being over the past few decades. Also, the construction sector's influence on climate change has been paid more attention. Accordingly, demands of environmentally friendly and sustainable structures have been rising rapidly, especially in Nordic countries where timber material has been strongly promoted in buildings and bridges.

There are several tools to investigate and assess the environmental impacts and sustainable potentials of a certain product or project; for instance, Life Cycle Assessment (LCA) as one of the most widely used approaches. In order to have an overview of the environmental performance of various timber bridges, this paper surveyed literature about LCA implementations on modern timber bridges and on bridges made of other materials as reference. Difficulties of LCA implementation on timber bridges are discussed. Earlier LCA studies are reviewed, in terms of assessment variances and quantitative results. However, it has been noticed that LCA implementations on timber bridges is quite limited. Meanwhile, this paper addressed key parameters, critical issues, challenges and possible improvement for the future LCA implementation.

LCA is an approach to compile and evaluate the potential environmental impact of a product throughout its life cycle. The results of a LCA are usually expressed by single score or multiple indicators, such as the global warming potential, the eutrophication potential and the ozone depletion potential. As a systematic tool, LCA has been widely applied in various fields such as industrial production, agriculture, food; as well as in construction sector. However, only a limited number of investigations are related to bridges, especially to bridges that contain toxic chemical preservative treatments. The construction sector contributes largely in the global environmental burden: presently it covers about 40% of the total energy consumption and 36% of CO_2 emissions in Europe (European Commission 2018). Meanwhile the Official Journal of the European Union (European Commission 2008) introduced the "polluter pays principle" and the "extended producer responsibility". Furthermore, they set a new target that shall be achieved by 2020 in European countries: 70% preparing for re-use, recycling and other recovery of construction and demolition waste. This clearly indicates the great importance of reducing environmental impacts within the construction sector, thus also for bridges that consume significant amount of construction materials and energy during its service life. Considering carbon storage and sustainability, timber as a natural material is a potential alternative to concrete or steel when building new bridges.

This paper presents the background methodology of LCA and reviews LCA studies on timber bridges as well as bridges made from other materials over the past few decades. The presented compilation of LCA implementations on timber bridges illustrates the variances among individual studies. The paper addresses main challenges for comparing existing LCA studies and highlights issues for further development of LCA on timber bridges. A streamlined framework based on the latest Eurocodes and standards for LCA on timber bridges is suggested.

2. LCA Methodology and streamlined framework

LCA is a technique to evaluate environmental impact of a product or project during its life cycle, the results are usually expressed by a single score or multiple impact indicators. A full LCA can provide holistic environmental understanding of a product along its lifespan, which starts from resource extractions (cradle) to final disposal (grave). However, in practice, conducting partial LCA is more common due to specific purposes determined by the practitioner, lack of information on the end-of-life of the product, and functional equivalency of compared LCA systems. For example, in comparative LCA studies on bridges, operational stage is typically identical for compared bridges (functionally equivalent), thus this stage is often excluded. In 1997, the International Organization for Standardization (ISO) published the first standard ISO 14040 (2006) for LCA and the second one ISO 14044 in 2006. Both standards provide principles, frameworks, requirements and guidelines of LCA for practitioners. Moreover, the ISO 14025 (2006) standard defines Environmental Product Declaration (EPD), and gives more precise rules for different types of products. This paper is based on the ISO standards (ISO 14025: 2006, ISO 14040: 2006, ISO 14044: 2006), European standard EN 15804 (2012) and ILCD handbook (EUR 24708 (2010)).

2.1 Four phases of LCA

The structure of LCA comprises four phases: (I) goal and scope definition, (II) inventory analysis, (III) impact assessment and (IV) interpretation.

Phase I - goal and scope definition

Determines the purpose of the study and its wideness and depth. The Functional Unit (FU) and system boundary are the most fundamental definitions, especially when comparing alternative designs for the same product. In ISO 14040: 2006, FU is defined as "*quantified performance of a product system for use as reference unit*". In existing LCA studies on bridges, frequently simplified definitions of the FU such as "1 m^2 effective bridge surface area through a lifetime of 100 years" are used, which enables the comparison between bridges, no matter the size, location or year of construction. However, such definition does not reflect the function of the investigated bridge (e.g. design load, average daily traffic) and implies that the material and energy consumption are assumed to be constant over the entire surface area. Accordingly, a direct LCA comparison between bridges based on a simplified FU has to be treated carefully.

Phase II - Inventory analysis

Identifies and quantifies the environmental inputs and outputs together with a product along its life cycle, where the Life Cycle Inventory analysis (LCI) shall be applied. LCI result is defined as "*outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment*". Data must be collected for each unit process within the system's boundary, where elementary flow and energy flow are the key components. Commercial and free LCI databases are available for diversified unit processes, which are the basic components of a product. Most common used LCI databases in the construction sector include Ecoinvent, European reference life cycle database (ELCD), World Steel LCI, etc.

Phase III - Impact assessment

Assesses and characterizes the LCI results obtained from Phase (II) into a set of environmental impacts. The impacts are categorised into classes, which represents "*environmental issues of concern to which life cycle inventory analysis results may be assigned*" (ISO 14040: 2006). The evaluation involves mandatory steps (classification and characterisation) and optional steps (such as normalisation and weighting). Currently, several life cycle impact assessment methods (LCIA) are available, such as CML 2002, Eco-indicator 99, EDIP, and ReCiPe.

Phase IV - Interpretation

Presents the environmental impacts results along with the defined goal and scope of the LCA study, also generates conclusions, suggestions, decision-making and reports. There is no standardised interpretation method; some interpretation methods belong to confirmatory category focusing on generating absolute conclusions, while others belong to the exploratory category.

2.2 Life cycle stages of bridges

When conducting LCA for a bridge, four life cycle stages may be considered: 1) material production stage: raw material extraction and product manufacturing of the bridge; 2) construction stage: transportation of materials and equipment to the construction site, installation of the bridge; 3) Operation and Maintenance (O&M) stage: use of the bridge during its service life; 4) End-of-Life (EoL) stage: starts when the bridge is replaced, dismantled or deconstructed, including demolition, transport, and waste processing.

LCA implementation on bridges require specialised knowledge of both LCA theory and bridge engineering. However, the focus and system boundary vary significantly among LCA studies in bridge engineering. So far, there is no specialised guideline or standards for applying LCA on bridges. Nonetheless, in the year 2012, a European standard EN 15804 (2012) was published for guiding LCA on construction products, where both buildings and bridges could be considered as complex construction products. The EN 15804 (2012) provides core rules for the product category of construction products and construction services, also describes life cycle stages and corresponding processes that should be considered in the EPD (which gains more attention and focus in the providers of construction products). In order to have LCA implementations on bridges more structured, this paper proposes a streamlined framework following the principles introduced in EN 15804 (2012) (see Figure 1). In the proposed framework, each life cycle stage consists of categorised sub-stages. When considering one individual bridge as one individual construction product, the framework facilitates systematic

LCA modelling; meaning that a specific name and clear defined sub-stages are associated to each life cycle stage. Using such a standardized and bridge-specific framework the LCA could be performed clearer, the analysis and the interpretation of the results would become more unambiguous; here it is referred to the list of critical aspects of LCA on timber bridges summarized in Section 3. For future LCA implementations on bridges, applying such a framework would also simplify the critical review process.

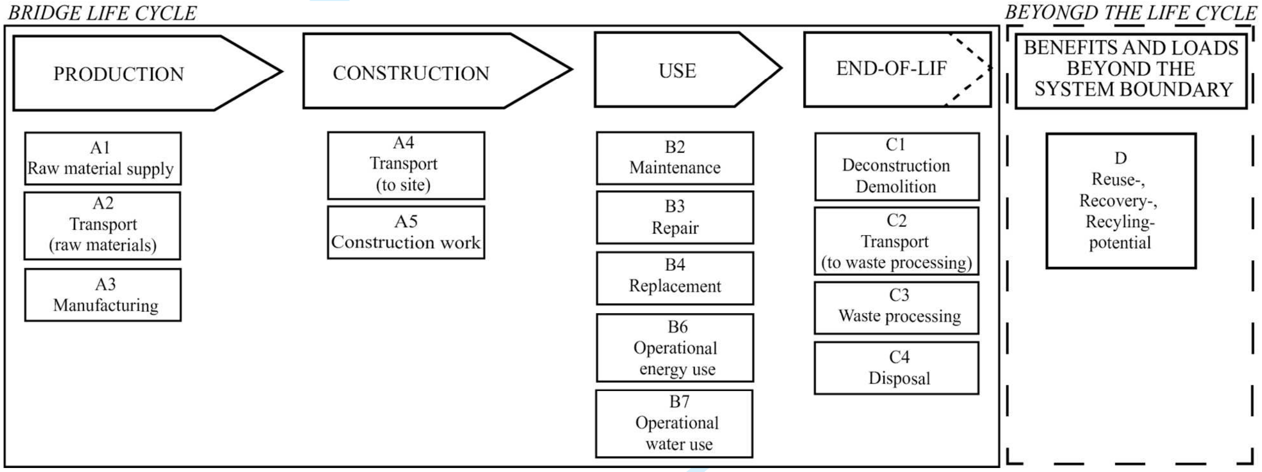

Figure 1. Streamlined LCA framework on timber bridges (in comply with EN 15804 (2012)).

2.3 *Environmental indicators and LCA tools*

The main difficulty of interpreting the LCA output is the variety of indicators, which largely depends on the chosen LCIA method. Each indicator has its own emphasis, and the user needs to choose the most important indicators and generate conclusions accordingly. Whether selecting all impact categories or single impact category (such as global warming potential) largely depends on the requirements of clients, although theoretically all categories should be considered. An example of common environmental indicators is presented in Table 1.

Table 1. Example of environmental impact specification (Salokangas (ed.) 2013).

Environmental Impact Category	Unit	Normalisation factor (eq. = equivalent)
Global Warming Potential	GWP	$8{,}92 \cdot 10^{-5}$ kg CO_2 eq.
Ozone Depletion Potential	ODP	45 kg CFC-11 eq.
Freshwater Eutrophication Potential	EP	2,41 kg P eq.
Fossil Depletion Potential	FD	$6{,}01 \cdot 10^{-4}$ kg oil eq.

Various LCA software and tools are available, which are generally for LCA implementations on all kinds of products. A simplified LCA tool especially designed for bridges, named as ETSI *BridgeLCA* has been introduced several years ago from ETSI project (Salokangas (ed.) 2013). It has embedded Ecoinvent database v2.1 and CML2001 (ReCiPe v1.06) method. However, it has limitations on material selections and assessment methods, also it does not use EN 15804 (2012) as reference or structural basis.

3. Critical aspects of LCA on bridges

In general, LCA is preferred to be used as a comparison tool, mainly due to the variety of both the assessment method and the input data such as consumed material quantities. When applying LCA on bridges, from the authors' perspective, critical issues can be categorised into two groups: aspects related to the LCA approach (LCA model, LCI database, LCIA method and the interpretation of the results) and aspects related to the bridge (structure and construction, transport distance, prediction of the structural performance). It has to be mentioned that, the listed issues might not be comprehensive.

3.1 LCA approach

ISO standards (ISO 14025: 2006, ISO 14040: 2006, ISO 14044: 2006) along with European standard EN 15804 (2012) and handbooks EUR 24708 (2010) set a framework, where also including multiple principles and guidelines for conducting LCA. However, LCA study is always case-specific; usually issues such as the scope, the system boundaries, the inventory and assessment selection, or the interpretation vary largely.

3.1.1 LCA model

No standardised model exists, even for one certain product system. The model is always case-specific or project-specific: for example, the LCA model for one timber bridge might differ from the one for another timber bridge. The reasons for such differences can be induced by context, completeness, comprehensiveness, preference, etc.

The LCA model is ideally created for the whole life cycle of a product system, but often LCA practitioners choose a specific life cycle range or exclude some parts due to clients' requirements or special comparison purposes. In addition, authorities' guidance or preference of certain emission categories would also have influence on LCA modelling. For example, the client asks for only CO_2 emission from material production and construction stages instead of the whole life cycle of the bridge. Thus, it needs more attention and consideration when creating a LCA model for one case. In order to make the model meet both the standards and the requirements of client's, the LCA practitioners shall thoroughly create and check their own models at the beginning of a LCA study.

Misunderstanding could be avoided by enhancing communication between the client and the LCA practitioner, as well with the model check and revision by LCA experts. For example, if the client has basic knowledge of life cycle stage specification of buildings based on specific standards (e.g., ISO 14040: 2006, EN 15804 (2012)), then the model structure and the required data would be clearer to both the client and the LCA practitioner. After establishing the model, crosscheck and revision from another LCA expert may better guarantee the model validity.

3.1.2 LCI database

There are several LCI databases and EPD reports from product suppliers available, either commercial or with open access. Their validity usually has a limited time frame, and may be updated regularly, since environmental emissions differ in years and factories. In the design stage, suppliers of certain product may not be determined, and the LCI data from different sources are influenced by technology, work force, and regional situations. For example, 1 m^3 glued laminated timber production causes 169,85 kg of CO_2 equivalent emission in in the US Pacific Northwest (Puettmann *et al.* 2013), while in Ecoinvent v2 Database it causes 223 kg of CO_2 emission (Salokangas (ed.) 2013). In addition, it should be noticed here that timber production consumption is composed by primary energy consumption and material related energy value (induced by combustion), which can be separated or combined together in different LCI databases. Accordingly, the corresponding energy consumptions may vary.

When using the LCI database, the LCA practitioner shall clearly understand the quantities for elementary flows and processes, in order to select the correct one and use it in the LCA model. Since, due to massive amount of the data in a LCI database, there are multiple options for the same elementary flow, which has spatial variability or manufacturing variability. Therefore, even within the same model, user input data and LCIA method; the LCA results may be diverged when applying different flows and processes in the same LCI database.

Earlier the LCA practitioner used only the available LCI data sets. If there were no data sets for certain flow or process in the chosen LCI database available, the practitioner would have either chosen similar ones or neglected them when they were of much less importance. The validity related to the values of LCI databases can be presented by the data quality assessment. Such data quality of the LCI databases was originally not included. In the past decade, some LCI database and LCA software providers introduced the evaluation of data quality system, e.g., the “pedigree matrix” created by Ecoinvent or the “data quality system” function that is embedded in openLCA software. Through these procedures, LCA practitioners can assess both the inventory data quality and their own input data quality. Correspondingly, it improves the transparency for both the LCI and the LCA results.

3.1.3 LCIA method

There are several LCIA methods that are widely accepted and used, but none of them has been verified as the only specialised method. Variances among LCIA methods include:

- Substances for a certain impact category,
- Characterisation Factors (CFs),
- “Cut-off” values (unrepresentative emissions are usually not reported in the LCI database).

Commonly, emissions enclosed in the LCI database are summed up per pollutant in LCIA methods, despite their geographical place of occurrence that is thoroughly considered in the LCI databases. Due to this relation between LCI and LCIA, it is suggested to the LCI providers for considering LCIA (especially endpoint method for toxicological assessment) or vice versa when reporting or documenting data, and pay attention to the geographical scale. Because, trace amount of one emission in LCI may have a huge CF, and it may result in a non-negligible even significant impact result in LCIA.

In general, LCIA method consists of mandatory steps: selection, classification and characterisation. Meanwhile, LCIA method grants the user optional steps: normalisation, grouping and weighting; those can be applied based on the goal and scope of the LCA study. These indicate that, the LCA practitioner must select, classify and determine characterisation factors for the chosen environmental impact categories. The optional steps significantly vary among the location of the analysis, requirements of clients, preference of LCA practitioners, etc. Therefore, LCIA method influences the results and can be affected for example by the location of the bridge, location of different material suppliers, characterisation of different emissions and weighting factors. One way to mitigating such effect is applying regionalised LCIA method, which has been tested by LCA case studies in agricultural sector (Rodríguez *et al.* 2014). However, applying the regionalised LCIA method can increase the accuracy of the bridge assessment, and associated with increasing modelling complexity. Therefore, it should be carefully considered before applying regionalised LCIA method.

3.1.4 Interpretation

ISO 14040: 2006 defines that interpretation phase shall summarise and discuss the results of an LCI or LCIA, or both, in order to reach conclusions and recommendations within the defined goal and scope of the study. Furthermore, limitations and assumptions of the study should be described. Regarding the interpretation of the LCA study on bridges specifically, there is a wide scope of opportunities to present the results; for instance, the results can be expressed by percentage or amount, by a single value or multiple values. An appropriate communication between the LCA practitioner and the client is necessary to ensure the results and demands match.

In order to ensure a reliable interpretation, it is advisable to apply several different interpretation ways. In case of unambiguous results, most of the applied interpretation ways lead to similar or even the same conclusion; otherwise, it is obvious that the conclusions might not clear or biased.

3.2 Bridge

In the aspect of bridge's input data to the LCA model, the quantity varies largely, which depends on the relative documentation from clients and material or product suppliers, LCA practitioner's estimation on bridge performance (e.g., the estimated maintenance and repair intervals) and the planned EoL scenario. Especially regarding the EoL stage, many LCA studies excluded this stage largely due to lack of data for the waste collection and processing.

3.2.1 Structure and construction

Quantity of the input data largely depends on the documentation obtained from the clients, in the aspect of both structural design and construction method. Mostly the clients provide primary drawings of the structural design, from which the quantity of materials can be calculated accordingly. However, for the construction method, actual quantity and validity of data are difficult to obtain. For instance, actual quantity of material consumed on-site, detailed construction method and duration, transportation methods and distances, energy consumption from machinery, etc. These data are usually neither well documented nor provided.

Moreover, the estimated construction time is associated with uncertainties and the material or product supplier might change. When conducting a LCA study on a newly built bridge, evaluation records of old bridges about material manufacturing, construction and maintenance can be considered as reference for estimation.

3.2.2 Performance

Information that is related to the past stage of the bridge may be collected from the bridge owner and operators. Information that is related to the future stage of the bridge, are largely depends on the performance of these reference bridges. However, the information has big influence on the input data such material quantities and fossil fuel consumption due to transportation.

Performance of the bridge during its life cycle shall be predicted and estimated based on the monitored condition values, testing values, empirical data from similar bridges, bridge degradation models for different components, or collected data from LCA calculations made by experienced experts. These estimations significantly influence the maintenance and repair of the bridge, accordingly influence the material and energy consumption (including transportation). More precise results can be achieved if a detailed Life Cycle Plan (LCP) would be available provided by the client.

In addition, in order to increase the durability of corresponding bridge components, some modern timber bridges are treated with hazardous substances such as Chromated Copper Arsenate (CCA) and creosote. However, in 2011, the European Commission recommended abandoning the industrial uses of creosote because of its toxicity, but member states can adjust the due date based on their own context (European Commission 2011). Retention of preservative substances treated in timber bridge components is problematic to inspect and predict. For example, there is neither measurement nor record of the actual creosote leakage nor the specific method to calculate the environmental impact of such leakage.

4. Literature survey of LCA studies on modern bridges

This paper aims at surveying literatures about LCA implementation on modern timber bridges, as well as on other bridges due to comparison reason. Note that the review is not complete but covers the most relevant LCA studies on timber bridges. The review is limited mainly to LCA studies on road bridges, which constitute the majority of all bridges. Only one LCA study on a pedestrian bridge has been found and included here. Railway bridges are excluded in this paper since they are not expected to be relevant to modern timber bridges. Comprehensive literature survey about railway bridges along with case studies could be found from Du (2015).

Additionally, literature about life cycle analysis has been conducted widely, from the aspect of cost, environmental impact, or both. Several literature investigations of the Life Cycle Cost (LCC) of bridges are documented (e.g., Salokangas (ed.) 2013, Hawk 2003, Gerold 2006, Rantala 2010, Morcous 2013). However, since this paper concentrates on the environmental impact in the life cycle (aka. LCA) of bridges, accordingly literature regarding LCC are not included in the review.

4.1 Reviews

Widman (1998) compared two road bridges during the whole life cycle by implementing LCA: a steel bridge with concrete decking in eight spans, and a steel I-girder bridge with concrete decking in single span. The paper focuses on both substructure and superstructure of the bridge, excluding marginal details of the joints and bearings. The data is collected from manufacturers in Sweden, Norway and Finland; and adapted to Swedish conditions. In order to compare, the unit is defined as environmental impact (as kg of certain emission) per square meter lane. The results indicate that production of cement and steel to be the main source of CO_2 emissions; the concrete material used in steel bridges contributes the major part to the environmental impact, meanwhile steel bridges need less material than concrete bridge; transportation of material induces a large amount of CO_2 and NOx emissions. Moreover, it is found that traffic during the use stage of the bridge is the most polluting source in the life cycle, while the environmental impact from the maintenance stage is negligible.

Itoh and Kitagawa (2003) compared two alternatives of steel girder bridges by using a modified life cycle methodology, in terms of CO_2 emissions and energy consumption. One is conventional bridge (CB), having seven longitudinal girders; the other is minimized girder bridge (MGB), having three longitudinal girders and minimised maintenance activities during 100-year service life. The life cycle consists of only construction, maintenance and replacement stages. In order to compare, the unit area of the bridge deck is chosen as the base, and the compared indicators are CO_2 emissions and costs. The results reveal that MGB solution has lower CO_2 emissions especially in the maintenance stage, CO_2 emission and cost of CB at the end of 120 years are higher than those of MGB. It is also found that differences of the environmental impacts could be doubled when the service lives are between 60 and 100 years. The influence of different replacement cycles of major bridge components for MGB and CB alternatives is also assessed, and three cases are considered: short service life, standard service life, and long service life. The paper concludes that the CB has higher CO_2 emission in all three cases of replacement cycles, and extending the service life of a bridge component is invaluable when considering total CO_2 emissions and life cycle cost. The environmental performance from superstructure and substructure at construction stage is then investigated on three design alternatives of a 120 m long bridge: prestressed concrete (PC) simple pre-tensioned T-girder, PC simple box girder, and steel simple non-composite box girder. The investigation reveals that the steel bridge has the highest environmental impact value, CO_2 emissions and energy consumption from construction equipment takes no more than 5% of the total amount. It is suggested that, in order to conduct the performance-based bridge design with considering LCA, more accurate durability information of each component of bridges may be necessarily required.

Kendall (2004) compared two bridge deck designs over a 60-year horizon: a conventional steel reinforced concrete (SRC) deck with mechanical steel expansion joints, and a SRC deck with engineered cementitious composite (ECC) link slabs. The applied LCA framework includes four phases: raw material acquisition, product manufacturing, product usage or consumption, and material waste. The environmental assessment focuses on the impact categories such as raw material consumption, energy consumption, criteria air pollutant, and greenhouse gas emissions. Reference datasets for materials are collected from Ecobilan's DEAM database, the Portland Cement Association (PCA), material's producers and the Association of Plastic Manufacturers in Europe (APME). The LCA results reveals that during the 60-year service life, the ECC system saves more than 50% in both material and energy compared to the conventional system, which primarily results from the reduced number of repair and reconstruction activities. In addition, it is verified that construction-related traffic is a key determinant of environmental impact.

Keoleian *et al.* (2005) conducted a comparative LCA between two bridge deck systems within 60-year service life. One deck system contains the conventional steel expansion joints, the other is a link slab using the ECC that aims extending the service life and reducing maintenance activities. The analysis excludes the initial construction process for both deck systems, but considers the traffic congestion during the construction stage. The results indicates that the ECC bridge deck system has significant advantages for all potential environmental impact: 38% less raw material consumption, 40% less total energy consumption, and 50% less solid waste generation. Moreover, the construction-related traffic congestion is identified to be the greatest contributor to most life cycle impact categories.

Steele and Cole (2005) conducted a LCA study for comparing three British bridge designs' environmental impact: a steel through deck, reinforcement concrete beam, brick arch structured. All these three bridge designs have similar service functionality, with approximate 10 m span, 40 tonne design load capacity and single lane carriageway capacity. The tool used for this environmental investigation is called Environmental Profiles, which is a LCA methodology devised by BRE (Howard *et al.* 1999). The applied indicator called Ecopoints is a measure of environmental performance that combines different environmental impact into a single score. Ecopoints is devised and based on UK situation, as well as weighting approach involving consultation from the construction industry. The results indicate that the single biggest cause of environmental impact during the life cycle can be attributed to construction (including material production in this study), by contrast, the activities associated with on-site structural fabrication have only limited burden. The paper claims that there is no consistently environmentally superior option among building materials such as brick, steel and concrete, even though the differences between the three materials clearly exist. The following influencing factors of environmental impact are also discussed: design efficiency, use of material, structure service life, the transport of materials to and from the construction site. The paper also concludes that environmental burden of traffic disruption and vehicle diversions could significantly contribute to the overall environmental impact of the bridge; and for existing bridges, it is generally environmentally better to maintain, refurbish or strengthen the structure instead of demolishing and rebuilding.

Collings (2006) outlined the range of embodied energy and CO_2 emissions for materials commonly used in bridges, but only dealt with two broad life cycle stages: construction and maintenance stages. Two studies are carried out, an initial study and a primary study. The initial study compares three alternative bridge designs related to the same site (a major crossing in the Middle East), which is derived from an actual project. It comprises a concrete cantilever bridge, a concrete cable-stayed bridge, and a steel arch bridge. The results of the initial study reveals that the steel bridge causes the highest CO_2 emissions; paint, waterproofing and plastic products results in high-embodied energy and CO_2 emissions per unit weight, although usually with small amount of usage in bridges. The primary study compares three alternative bridges: a profiled girder, a tied arch, and a cable-stayed. Besides, three primary materials: concrete, steel, steel-concrete composite are considered for each of the three forms, thus nine bridge alternatives in total. The results reveal that concrete bridge alternatives have the lowest embodied energy and CO_2 emissions, but the embodied energy consumption was only studied in the construction stage while the CO_2 was included in both construction and maintenance stage. General conclusions from the study are: material selection is a key issue to achieve lower environmental burden for longer span bridges, CO_2 emissions during maintenance and repair stage are slightly larger but of similar magnitude to construction stage, the main cause of additional CO_2 emissions comes from resurfacing of the bridge and the traffic delay during the maintenance and repair stage. In order to reduce environmental burdens of a bridge, some solutions and attentions are addressed: minimizing materials and well-tried structural principles in the design phase, minimizing joints and bearings in the ongoing phase of the bridge; environmental burden of a bridge is approximately proportional to cost.

Gervásio and da Silva (2008) presented an integrated life cycle methodology of LCA and LCC, considering both environment and economic aspects. The methodology is applied on a three-span continuous bridge with two solutions: steel-concrete composite (I-girder), to compare with a prefabricated prestressed concrete (U-girder). The comparison is restricted to the superstructure, and both solutions are considered to have 50-year service life. In the LCA analysis, the life cycle is restricted only to the construction stage due to lack of data. Data of concrete production is obtained from the Portland Cement Association, and three types of concrete mixes are evaluated. For the total environmental impact from the results, the steel-concrete composite bridge solution has better environmental performance than the prestressed concrete solution. However, it also indicates that both solutions have rather similar global warming potential.

Horvath (2009) presented several critical issues when applying the LCA in the bridge analysis. The paper claims that the definition of FU should not be too narrow; and in order to make an optimal decision, a full life cycle from the planning phase until the EoL phase shall be included. It also highlights the importance of the time horizon during the long life of the bridge, and the influence of location of the analysis such as local characteristic of material, labour, technologies and so on. Furthermore, it is suggested that a good LCA should quantify all environmental emissions and waste instead of only greenhouse gas; and interpretation of the LCA results should not be worked as recommendations, but step forward to make an impact for decision and policy makers.

Bouhaya *et al.* (2009) conducted a simplified LCA on an innovative road bridge made of timber beams and ultra-high performance concrete (UHPC) deck. The bridge deck has a 25 m span, 10 m width including two lanes, and withstand the medium flow rates of lorries. The UHPC deck is 7 cm thick, fastened on fourteen timber beams with 51 cm clear-space interval. The assessed factors are only energy use and CO_2 emission, from cradle to grave in the 100-year lifespan. Life cycle phases consist of material production, transportation, construction, maintenance and EoL. The FU is defined as a 25 m span bridge deck in its lifespan. Material data for each life cycle phase is presented with details and assumptions. For the production phase, the applied LCI profiles include EPDs for timber and concrete wall, and LCI database (by International Iron and Steel Institute IISI) for engineering steel. For the transportation phase, transportation of timber beams and UHPC slab from the factory to the site is considered. The LCI data about energy consumed in the transportation phase is calculated based on the French Standard FD P 01-015 (2006) and ISO 14040: 2006, ISO 14044: 2006. For the construction phase, the energy consumption and CO_2 emissions come from the on-site machinery such as mobile crane and generators, and they are assumed to be the same as in the construction phase. For the maintenance, the deck elements are assumed to be individually replaced. The UHPC deck is regarded as a component lasting 100 years without maintenance, while the timber beams are assumed to be replaced during the life cycle. For the EoL phase, the demolition of the structure and the waste treatment are considered: three EoL treatment scenarios for timber are studied and compared. The LCA results indicate that the material production phase takes the main part of the energy use and has the highest proportion of the total environmental impact and the biomass CO_2 of wood has positive environmental impact. For the material production, the renewable energy is about 70% of the production energy. EoL timber recycling scenario results in the lowest impact on CO_2 emissions even considering large uncertainties, while EoL timber burning scenario (despite its remarkable energy impact) is the worst option in terms of CO_2 emissions. However, the paper addresses that burning wood in the EoL phase could cause more CO_2 emissions compared with natural gas combustion but require less primary energy, then concludes that there is no winning scenario on these two impacts.

Lounis and Daigle (2010) discussed some performance indicators that can be used for life cycle design of highway bridges in North America. An example is presented, including illustration of how different design and rehabilitation approaches can influence the desirable balance between social, economic and environmental sustainability criteria. In the aspect of environmental sustainability, an LCA calculation was conducted for comparing two bridge deck designs: high performance concrete (HPC) and normal performance concrete (NPC) bridge deck. The results indicate that the service life for the HPC deck alternative with Supplementary cementitious materials (SCMs) is almost twice as the NPC deck's service life. In the aspect of material related contribution to the environmental impact, three major elements are chosen to depict differences between the two alternatives: cement production, additional transportation needed for the SCMs included in the HPC mix, and CO_2 emitted by cars/trucks delayed due to the maintenance, repair, and replacement activities. The results reveal that cement production effects largely in CO_2 emissions, but additional transportation and differences between emissions due to traffic disruption is not very significant. It also concludes that CO_2 emissions of the HPC deck is about one third of the NPC deck's, mainly due to the lower cement consumption of the HPC mix that using supplementary cementing materials, as well as the increment in traffic disruption due to earlier replacement of NPC deck which has shorter service life. In addition, volume of construction waste material from NPC deck alternative is found to be nearly three times of the HPC alternative.

Rantala (2010) carried out LCA study on three Finnish standard bridges by using ETSI *BridgeLCA* tool (Salokangas (ed.) 2013), as well calculated LCC according to Finnish Transport Agency's instruction (Tiehallinto 2008). The compared standard bridge types are steel reinforced cantilever slab bridge, composite beam bridge with steel reinforced concrete deck, and prestressed concrete beam element bridge. All three bridges have a superstructure length of about 20 meter, where the cantilever bridge has the shortest length. The LCA calculation is performed by considering material amounts used for bridges during the construction, maintenance and repair stages. Transportation of workers and goods is excluded due to challenging evaluation. Six environmental impact categories are assessed: ADP, AP, EP, GWP, ODP, and POCP. The results are calculated by applying weighting factors, according to the United States Environmental Protection Agency's factors (Salokangas (ed.) 2013). The environmental impacts per deck square meter are compared and indicate that, the steel reinforced concrete cantilever slab bridge has the best environmental performance, while the steel reinforced concrete deck composite bridge has the worst environmental performance. However, it is also addressed that the differences are insignificant due to the small size of all three bridges, and the compared LCA results may be sensible for large bridges.

Hammervold *et al.* (2013) conducted LCA studies on three bridges built in Norway, all three bridges were made of different materials. The LCA tool applied is developed according to ISO standards, with using CML as LCIA method and Ecoinvent as LCI database. The three bridges are: 42,8 m steel box-girder bridge, 37,9 m timber arch bridge and 39,3 m concrete box-girder bridge. The arch and deck of the timber bridge are salt-impregnated and creosote-impregnated respectively, however, creosote leakage is not considered in the LCA calculation due to lack of method and valid data. The whole life cycle of the three bridges are considered: material production, transportation of materials and personnel, construction, operation (excluding traffic disruption), maintenance, repair and EoL. Main structural components, machinery construction equipment and a series of maintenance actions are the major inputs of LCA calculation. Six impact categories of midpoint indicators are selected: GWP, ADP, AP, POCP, EP, and ODP. In order to simplify the comparison, those midpoint results are normalised and weighted to get a single score, and the FU is defined as "1 m^2 effective bridge surface area through a lifetime of 100 years." The results reveal that GWP, ADP and AP are the main impact categories. The concrete bridge among the three investigated bridges is identified as the best environmental-friendly solution, while the steel bridge has the worst environmental performance.

However, the results reveal that if only comparing GWP category, the timber bridge leads to the lowest value among the three investigated bridges. Moreover, production of materials from the main load carrying systems accounts for the main share of the total environmental impact, due to the large quantities of materials required. Construction stage has marginal contribution to the total environmental impact, compared to other life cycle stages. Bridge equipment such as waterproofing, the asphalt layer, and the parapet accounts for 10-15% of the impact in each category. Moreover, the superstructure of the timber arch bridge here is found not to be the dominant part as other bridges that having concrete or steel as the main load-carrying material, but it has similar contribution as bridge equipment's to the three major environmental impact categories. The paper also addresses the importance of diesel consumption in the construction stage and the traffic disruption effects in the use stage caused by repair and maintenance.

Hettinger *et al.* (2015) carried out LCA applications on two bridges: a composite bridge and a prestressed concrete bridge. The study is based on LCA standard and reviewed by external experts from consulting group PE International. Eleven LCA common indicators are chosen to comprise the environmental profile of the bridge, such as GWP, AP, EP, ODP, and so on. CML method is applied for evaluating the environmental impact, but without primary energy demand and water competition. Some steps of the life cycle are excluded: finishing steps of steel elements, erection of the bridge and its use phase that are same for both bridges. LCI of steel is based on information from WorldSteel and some European studies, the recycling rate for steel section and reinforcing steel is set separately. LCI of concrete is based on two studies and discussion with internal experts, the EoL scenarios for concrete from reinforced-concrete waste is chosen**,** where 35% reinforced-concrete is directly sent to landfill. Regarding material transportation, both steel and concrete elements are assumed to be transported by truck only. The results indicate that composite bridge has significantly smaller environmental burdens than the other bridge, recycling may not necessarily reduce the environmental burdens as the cost of recycling may be higher than the benefits coming from it, there is a connection between the mass of the bridge and the environmental burdens. In addition, the paper addresses that the production phase (from extraction of raw materials to semi-finished products) is the most important among other phases for most environmental indicators. For example, the production phase is identified to be the main contributor to GWP and seven other indicators, while EoL phase contributes much more for ODP and three other indicators to the overall results; and this is related to the treatments in the sorting plant that has a large effect on these particular indicators.

Niu and Salokangas (2016a) carried out a LCA study on a truss timber highway bridge in Finland. The study is based on ISO standards and considers only the superstructure of the bridge. Ecoinvent database is applied as LCI data, CML method is applied as LCIA method, where five LCA common impact indicators are selected, such as GWP, AP, and ODP. FU in this study is defined as “1 m^2 effective bridge area for traffic in Finland during 100 years of designed service life”. Timber material is considered as carbon-neutral. Timber without creosote treatment is assumed to be 100% material recycled in the EoL. Creosote leakage of bridge components and consequential environmental impact are not considered. The study investigates the maintenance records of timber road bridges, collected from the bridge register system of Finnish Transport Agency, and maintenance activities applied in the investigated bridge are based on those records. The results indicate that the investigated bridge has the most environmental impact on the category of EP, and the least environmental impact on ODP category. Maintenance intervals affects the environmental impact and energy consumption in a relatively small range, when assuming no harm on the structural behaviour. Major material of the bridge consumes more energy than others, material production stage takes the biggest share of the total environmental impact. Bridge lighting influences on the total energy consumption and shall be included for long span bridges.

Niu and Salokangas (2016b) carried out a LCA on a timber pedestrian bridge in Finland: a simple girder bridge in rural area. The study considers only the superstructure of the bridge. Ecoinvent database is applied as LCI data, CML method is applied as LCIA method, where five LCA common impact indicators are selected, such as GWP, AP, and ODP. FU in this study is defined as “The whole bridge area during 50 years of designed service life”. In the EoL stage, sawn timber waste is assumed to be 80% for material recycling and 20% for energy recovery (incineration). Timber is conservatively considered as “carbon-neutral”, meaning the biogenic carbon sequestration and emissions of wood are excluded (Ruuska (ed.) 2013). The study investigates the maintenance records and maintenance activities of timber pedestrian bridges, collected from the bridge register system of Finnish Transport Agency. It is found that the location of the bridge influences the requirements of maintenance actions, for example, bridges in southernmost Finland have higher probability of maintenance than those in northernmost Finland. The results indicate that the investigated bridge has the most environmental impact on the category of EP, and the least environmental impact on ODP category. Material production stage takes the biggest share of the total environmental impact in all five selected impact categories. Contribution of environmental impact from construction stage is hardly to see, since most components are prefabricated, thus less on-site work is required. Operation and maintenance stage is found to be contributing less than one tenth of the total environmental impact. Besides, standardised LCA modelling and criteria for timber bridges are preferred.

Penadés-Plà *et al.* (2017) presented a methodology to conduct LCA for reinforced concrete bridges. The study compares two optimal post-tensioned concrete box-girder road bridges with different maintenance scenarios by using LCA, both located in the coastal area of eastern Spain. The first scenario is referred using concrete with a characteristic strength of 35 MPa and having two maintenance periods, while the second scenario is referred using concrete with a characteristic strength of 50 MPa and having only one maintenance period. ReCiPe method are chosen to conduct the assessment, along with midpoint approach (including 18 environmental impact categories) and endpoint approach (including three damage categories). It is assumed that 71% steel is recycled and used in the manufacturing phase to form a closed loop, and the concrete is crushed and left to landfill to be completely carbonated. In addition, benefit from the carbonation of the concrete is considered. The results of using midpoint approach reveal that for both scenarios, all impact categories contribute the most in the manufacturing or use and maintenance stages, over 50% GWP comes from the manufacturing stage. The first scenario causes lower environmental impact in the manufacturing stage, but is two times of the second scenario during the use and maintenance stage. However, the paper concludes that a better design with less maintenance activities can reduce the global warming impact. The results indicate that GWP category has the highest variation in the manufacturing stage. Nevertheless, the variation in the use and maintenance stage is generally higher than in the manufacturing stage. The endpoint approach offers an easier-interpreted result by summarising the midpoint results, and addresses the importance of considering the whole life cycle. Moreover, the first scenario is found to have 13.3% higher global warming contribution than the second scenario.

Niu *et al.* (2017) conducted a LCA study on two timber design alternatives of Driva Bridge built in Norway. Both design alternatives are network arch type, the timber material is considered as carbon-neutral, with assuming that no chemical treatment would be applied. FU is defined as “bridge effective area within the 100-year service life”. Two EoL scenarios of timber are studied: 100% energy recovered and 100% put into demolition. Five environmental impact midpoint indicators are chosen. The results show the distribution of environmental impact during energy consumption, indicate that EP and FP are the most dominant impact categories, while ODP is the most insignificant category. However, the results are sensible to different weighting factors for the categories. The EoL scenarios of timber largely influence the environmental impact proportion of EoL stage among the whole life cycle. The preferred EoL of timber is to be 100% energy recovery. The results also reveal that the major construction materials are the key factors to influence the total environmental impact and energy consumption, especially steel. The steel quantity could significantly change the total environmental impact.

Zhang *et al.* (2016) presented an investigation about uncertainty of bridges’ LCA. A probability-based method is applied for a case bridge in China, with the scope of cradle-to-grave. The uncertainty and inaccuracy of LCA are investigated in two aspects: quantitative analysis of LCI uncertainty (mainly comes from the lack of data and data inaccuracy), uncertainty propagation in the LCIA by using Monte Carlo simulation. In addition, sensitivity analysis is presented to evaluate the relationship between LCA results and relevant data sources such as resource and energy consumption. The paper concludes that establishing a reasonable maintenance strategy is crucial to reduce the uncertainty for the estimation of bridge’s environmental impact. Weighted values for different environmental impact midpoint indicators have great influence on the Endpoint indicators.

4.2 Summary of the literature survey

The literature survey reveals that, there is neither specialised criteria nor threshold that a bridge should fulfil in the aspect of environmental impact; there is no clear vision of environmental performance of timber bridges due to limited number of investigations.

Among these LCA implementations, the model, goal and scope, inventory and assessment method reflect a huge variety. Interpretations also vary: some studies compared different environmental impact categories by percentage, while others compared them by corresponding equivalents' amount. Table 2 shows the reflection from the surveyed literatures. It reveals that in earlier studies the LCI database were not always clearly mentioned. The applied LCIA method are either unknown or totally differed, and there is no preference on the method selection. Regarding interpretation, the results and enclosed impact categories are arbitrary. For example, most surveyed literature focused on merely CO_2 emissions and energy consumptions, without considering other impact categories. Moreover, sensitivity analysis that is required in ISO 14040: 2006 is mostly excluded in the interpretation phase in several studies. Few LCA studies conducted sensitivity analysis, such as comparison of different maintenance scenarios or EoL scenarios and input parameters.

Table 2. Variation reflected in the literature survey.

Reference	LCI database	LCIA method	Interpretation ways
Widman (1998)	Data provided by manufacturers in Sweden, Norway and Finland	EPS, Environmental Theme Method, Ecoscarcity Method.	Distribution of various emissions and energy use (by percentage)
Itoh and Kitagawa (2003)	Data provided by manufacturers	Unknown	Distribution of CO_2 emissions and energy use (by percentage)
Kendall (2004)	Portland Cement Association, DEAMTM[1], IISI[2] 2000 steel data, Ecobilan (Ecobilan 2001),other LCI data provided by industry and manufacturers	Unknown	Material and energy consumption, 3 pollutants/emissions, sensitivity analysis
Keoleian *et al.* (2005)	Portland Cement Association, DEAMTM[1], IISI[2] 2000 steel data, other LCI data provided by industry and manufacturers	Unknown	Distribution of various emissions and energy use (by amount), sensitivity analysis
Steele and Cole (2005)	Unknown	Ecopoints	Design efficiency and various construction functions (by single Ecopoints)

Collings (2006)	Unknown	Unknown	Distribution of CO_2 emissions and energy use (by amount)
Gervásio and da Silva (2008)	Portland Cement Association, IISI[2]	Environmental Problems approach	12 impact categories presented by amount (normalised and weighted)
Bouhaya *et al.* (2009)	EPD of the glulam girder[3], EPD of the concrete wall[4], IISI[2]	Unknown	Distribution of CO_2 emission and energy consumption (by amount), sensitivity analysis mentioned
Lounis and Daigle (2010)	Unknown	Unknown	Distribution of CO_2 emission and landfill use for waste materials (by amount)
Rantala (2010)	Ecoinvent (Ec(Lounis and Daigle 2010)oinvent 2008)	CML (CML 2001)	Distribution of 6 impact categories (normalised and weighted)
Hammervold *et al.* (2013)	Ecoinvent (Ecoinvent 2008), collected data	CML (CML 2001)	Distribution of 6 impact categories (by percentage, normalised and weighted), sensitivity analysis
Hettinger *et al.* (2015)	LCI of WorldSteel 2010, Ecoinvent database (Ecoinvent 2011), others from INRETS and GaBi database	IPCC	Environmental profiles by 11 indicators comparison (by percentage), CO_2 emission comparison (by amount).
Niu and Salokangas (2016a)	Ecoinvent (Ecoinvent 2008)	CML (CML 2001)	Distribution of 5 impact categories and energy consumption (by percentage), sensitivity analysis
Niu and Salokangas (2016b)	Ecoinvent (Ecoinvent 2008)	CML (CML 2001)	Distribution of 5 impact categories and energy consumption (by percentage)
Penadés-Plà *et al.* (2017)	Ecoinvent	ReCiPe	Distribution of 18 impact categories (midpoint) associated with uncertainty analysis, and 3 endpoint indicators
Niu *et al.* (2017)	Ecoinvent (Ecoinvent 2008)	CML (CML 2001)	Distribution of 5 impact (normalised and weighted) and energy consumption (by percentage), sensitivity analysis

[1] Ecobilan's Database for Environmental Analysis and Management
[2] the International Iron and Steel Institute
[3] By French Environmental Protection and Energy Management Agency
[4] By SNBPE (Le Syndicat National du Béton Prêt à I'Emploi)

In order to have a more intuitive vision on the surveyed literature, the results of individual studies are summarized in Table 3, including the CO_2 equivalent's values and energy consumption per FU, which are the most documented results. However, some literatures introduced earlier are not included as only percentage values or rough amount, instead of specific values have been provided. Therefore, the CO_2 equivalent values obtained from these literatures are difficult to compare.

Table 3 clearly shows that, LCA studies on bridge vary significantly and bridge-specific. Most studies are related to road bridges, only one study is about pedestrian bridge. The reviewed LCA studies consist of three major bridge types that are girder, arch, and cable-stayed bridges. Sizes of the investigated bridges vary significantly, bridge deck areas range from 50 m^2 to 4300 m^2. The bridge deck area seems to have an influence on the results per FU, however, the definition of effective bridge deck area varies. Design service life of the bridge varies between 50 and 120 years, and life cycle stages were either entirely included or partly included. Timber was mostly considered as carbon-neutral, only one study considered the carbon storage of it. The EoL scenarios of construction materials especially wood material vary, usually it is considered as incineration or material recycled. CO_2 indicators are expressed differently, by midpoints, normalised, weighted values, or not specified. Even though many parameter between the case study are different, Table 3 indicates few general conclusions such as, 1) compared to concrete and steel bridge alternatives, timber offers relatively better environmentally performing solutions when considering only CO_2 emission; 2) for girder bridge type, concrete alternatives lead to more CO_2 emissions per FU, compared with steel alternatives; 3) for arch bridge type, timber bridges cause lower energy consumption per FU; 4) larger bridge deck area tends to causes lower energy consumption per FU.

4.3 Discussion about the literature survey

The literature on timber bridges shows that, the proportion of other construction materials than timber plays an important role. For example, steel applied in timber bridges consumes vast energy and induces much more CO_2 emissions than timber. According to EN 15804 (2012), if the bridge is built by using the virgin steel (occurred in the production stage of the bridge), although steel is considered to be 100% recycled, such benefit belongs to the next life circle if the recycled steel is not used in the same bridge life cycle (closed-loop), thus cannot be counted in the present life cycle of the investigated bridge. However, if the bridge is built by using the recycled steel, the benefit of recycling steel will be counted for the current investigated bridge (occurred in the production stage of the bridge). In practice, having recycled steel or concrete applied in the load-bearing members of bridges is challenging due to quality requirements. Therefore, substituting steel by timber can drastically reduce the CO_2 emission and energy consumption.

The review also shows that, whether and how considering carbon storage of wood has not been unanimously agreed, and the consideration of carbon benefit over time has gained more attention. For example, the biogenic carbon emissions and carbon sequestration are excluded in the carbon footprint values, according to European ECO2-approach where carbon footprint is expressed in terms of CO_2 equivalent (CO_2 eq.) (Ruuska (ed.) 2013). In other words, in Europe, it is conservative to assume “carbon-neutral” for wood material.

From the material or building aspect, there are plenty of literatures regarding CO_2 and energy analysis of wood applied as construction material. For instance, challenges and concerns of wood substitution in construction are discussed in (Kotaji *et al.* 2003); e.g., the time of harvesting, wide array of wooden products, and relation between forest management and environmental services. Gustavsson and Sathre (2011) and Sathre *et al.* (2012) reviewed and commented previous studies on the wood substitution in construction, found two crucial factors: FU and system boundaries. They also recognised the complexity of dual role of wood as both material and fuel.

Timber as material is considered to be eco-friendly and could contribute to the mitigation of global warming, but it may also cause CO_2 emissions in the EoL stage. At present, the after-life of timber construction waste from bridges has not yet been explicitly studied. For example, many old timber bridges are with hazardous preservative treatments such as CCA and creosote. How and where to deal with such toxic waste material are lack of documentation or study.

Therefore, whether such waste treatment would mitigate CO_2 and other emissions or not is ambiguous. It needs validation by investigating and conducting more LCA studies on this issue.

5. Summary and recommendations

This paper presents a literature survey on LCA implementations of modern timber bridges and bridges made of other materials. It has to be considered that LCA implementations on bridges are always case-specific, and usually associated with limitations and assumptions. Accordingly, general findings and common conclusions are limited. Nevertheless, some general issues and recommendations, relevant to the LCA implementation of timber bridges in the early stage, are found:

- Prior to the LCA analysis, uniformed judgement criteria, implementation guideline and qualification requirement of LCA implementations on bridges shall be determined and illustrated by both the customer and the practitioner.
- Sensitivity analysis should be taking into account for the interpretation of the LCA results, at least for the most relevant parameters.
- Critical reviews are always needed, not only to verify whether an LCA study meets the purpose or requirement from clients, but also to facilitate understanding regarding the credibility of LCA in general.
- The implementation of full LCA studies are generally advised, however, for specific cases partial LCA studies based on special requirements might be acceptable.
- Functional unit and system boundary should be cautiously determined at the beginning of an LCA study.

- A wide range of indicators shall be considered instead of focusing only on CO_2 emission and energy consumption.
- Updated LCI database and the available Environmental Product Declaration documents are preferred to be applied.
- The consideration of carbon storage of wood material needs to be carefully treated. Depending on the main purpose of the investigation, it might be useful to consider both alternatives (with and without considering carbon storage).
- Material production stage shall be considered carefully, since it is usually identified to contribute the largest share of environmental impact.
- It is recommended that LCA studies on timber bridges consider the influences of manufacturers' location , traffic disturbance and disclosure during the maintenance stage,
- Durability and degradation of timber bridges including maintenance plan and management are advised to be carefully considered.
- Different End-of-Life scenarios of timber bridges, such as demolishment method and timber waste management, should also be investigated. Especially for toxic waste such as chromated copper arsenate and creosote-treated timber waste, detailed processing flows are necessary.

Considering the current tendency of sustainable construction and requirement of reducing CO_2 emissions and energy consumptions, LCA implementation on bridges will become more important. In the future, comprehensive and well-performed LCA studies should be used as supportive and decisive tools for evaluating different bridge alternatives, including the material choice of the structural members.

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Table 3. Compilation of selected LCA applications on modern bridges.

Reference	General info of bridge			LCA calculation related content				LCA results	
	Material[A]	Type of the bridge	Designed service life (years)	Life cycle stages	Effective bridge deck area (m^2)	Carbon storage of wood	EoL[B] scenario of timber/concrete/steel	Carbon emissions per FU[C] (kg CO_2 eq.)	Energy consumption per FU[C] (MJ)
Itoh and Kitagawa (2003)	Concrete	Prestressed concrete simple pre-tensioned T-girder	N.A.[D]	construction	1800	N.A.	Excluded	179	$7{,}05 \cdot 10^3$
		Prestressed concrete simple box girder	N.A.[D]	construction	1800	N.A.	Excluded	161	$6{,}98 \cdot 10^3$
	Steel	Simple non-composite box girder[E]	N.A.[D]	construction	1800	N.A.	Excluded	299	$13{,}47 \cdot 10^3$
Collings (2006)	Concrete	Girder	120	construction[F] and use	4300	N.A.	Excluded	2457	$30{,}6 \cdot 10^3$
	Concrete	Arch	120	construction[F] and use	4300	N.A.	Excluded	4005	$49{,}1 \cdot 10^3$
	Concrete	Cable-stayed	120	construction[F] and use	4300	N.A.	Excluded	3726	$43{,}9 \cdot 10^3$
	Steel	Girder	120	construction[F] and use	4300	N.A.	Excluded	2810	$39{,}3 \cdot 10^3$
	Steel	Arch	120	construction[F] and use	4300	N.A.	Excluded	4326	$61{,}9 \cdot 10^3$
	Steel	Cable-stayed	120	construction[F] and use	4300	N.A.	Excluded	3822	$50{,}6 \cdot 10^3$
Gervásio and da Silva (2008)	Concrete	Prestressed box girder (only concrete part)	50	construction	2664	N.A.	Excluded	54	$0{,}37 \cdot 10^3$
Bouhaya *et al.* (2009)	Timber	Girder (with UPHC[G] deck)	100	whole	250	Yes	Timber landfill	-7	$11{,}32 \cdot 10^3$
						Yes	Timber incineration (for energy heating)	101	$7{,}44 \cdot 10^3$
						Yes	Timber recycling	-72	$11{,}32 \cdot 10^3$
Rantala (2010)	Steel-reinforced concrete	Cantilever slab[H]	100	construction and use	142,5	N.A.	Excluded	988[I]	Excluded
	Steel-reinforced concrete composite	Deck composite[H]	100	construction and use	150	N.A.	Excluded	1108[I]	Excluded
	Prestressed concrete	Beam element[H]	100	construction and use	150	N.A.	Excluded	1068[I]	Excluded

Hammervold *et al.* (2013)	Steel	Box girder[E]	100	whole	321	N.A.	Steel recycled (100%)	790[J]	89,95[I]
	Timber	Arch[E]	100	whole	229	carbon-neutral	Timber incineration (for energy usage, 100%)	550[J]	92,8[I]
	Concrete	Box girder[E]	100	whole	417	N.A.	Concrete reused (as filling material, 100%)	600[J]	95,90[I]
Niu and Salokangas (2016a)	Timber	Girder (pedestrian bridge[L])	50	whole	50,2 (effective width · total bridge length)	carbon-neutral	Sawn timber: 80% of material and 20% of energy recycled Glulam: 100% material recycled	1470[J] (0,131[I])	$86,65\cdot10^3$ (largely from transportation of material & personnel)
Niu and Salokangas (2016b)	Timber	Truss[L]	100	whole	2548 (effective width · total bridge length)	carbon-neutral	Glulam: 100% material recycled. Creosote treated glulam: 100% to waste plant	578[J] (0,051[I])	$16,6\cdot10^3$
Penadés-Plà *et al.* (2017)	Reinforced concrete (35 MPa concrete)	Post-tensioned concrete box girder	150	whole	1350 (width · span length	N.A.	Steel recycled (71%) Concrete landfilled (100%)[M]	594[N]	Excluded
	Reinforced concrete (50 MPa concrete)	Post-tensioned concrete box girder	150	whole	1350 (width · span length	N.A.	Steel recycled (71%) Concrete landfilled (100%)[M]	510[N]	Excluded
Niu *et al.* (2017)	Timber	Network Arch_Design1[L]	100	whole	1326,45 (effective width · span)	carbon-neutral	Glulam: 100% energy recovered	665[J] (0,059[I])	$24,8\cdot10^3$
						carbon-neutral	Glulam: 100% into demolition	884[J] (0,079[I])	$24,4\cdot10^3$
	Timber	Network Arch_Design2[L]	100	whole	1326,45 (effective width · span)	carbon-neutral	Glulam: 100% energy recovered	988[J] (0,088[I])	$30,0\cdot10^3$
						carbon-neutral	Glulam: 100% into demolition	1200[J] (0,011[I])	$29,6\cdot10^3$

[A] The material for the main load-carrying members
[B] End-of-Life
[C] Functional Unit: unit effective bridge area during the bridge's life cycle

[D] Commonly believed to be 60-year service life
[E] The whole bridge structure including superstructure, substructure, etc.
[F] Construction stage here includes the material production
[G] Ultra High Performance Concrete
[H] Foundation and substructure were included
[I] Normalised results based on the calculated midpoint results
[J] Midpoint results
[K] Only by machinery, diesel (litre) converted into MJ (source: IOR Energy: List of Common conversion factors (Engineering conversion factors). Retrieved 2008-10-05)
[L] Only superstructure of the bridge
[M] Concrete is assumed to be completely carbonated
[N] Bridge area is calculated by span length · width

Table 1. Example of environmental impact specification (Salokangas (ed.) 2013).

Table 2. Variation reflected in the literature survey.

Table 3. Compilation of selected LCA applications on modern bridges.

Figure 1. Streamlined LCA framework on timber bridges (in comply with EN 15804 (2012)).