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**Title: Environmentally sustainable bridge solution from a maintenance perspective**

Author 1

* Teslim B. Balogun, BSc, MSc
* Department of Architecture and Built Environment, University of the West of England, Bristol, United Kingdom

[Teslim2.Balogun@live,uwe,ac.uk](mailto:Teslim2.Balogun@live,uwe,ac.uk)**, Tel 01173286494**

Author 2

* Adrienn Tomor, PhD
* Department of Architecture and Built Environment, University of the West of England, Bristol, United Kingdom

Author 3

* Jessica Lamond, PhD
* Department of Architecture and Built Environment, University of the West of England, Bristol, United Kingdom

Author 4

* Hazeem Gaoza, PhD
* Department of Architecture and Built Environment, University of the West of England, Bristol, United Kingdom

Author 5

* Colin A. Booth, PhD
* Department of Architecture and Built Environment, University of the West of England, Bristol, United Kingdom

**Abstract**

The maintenance phase is crucial in determining a sustainable structure. Bridge maintenance contributes to sustainable development matters emerging from cost and environmental impact associated with various maintenance activities. Comparisons have been made between different bridge structural form, based on materials, components and construction method, but less information is available on bridge maintenance activities to help decide a sustainable structural form. Concrete, steel and masonry bridge maintenance activities was considered in this study to reveal the structural form with more sustainable maintenance qualities on the basis of their material, energy and transportation impact on human health, ecosystem and energy. Masonry bridge emerged more sustainable on the account of life cycle environmental impact of its maintenance activities. Concrete and steel bridge emerged least sustainable. The paper concludes that masonry bridge should be considered more for new structural solutions rather than the automatic preference for concrete and steel options

**Keywords**

Bridge; sustainability; life cycle assessment; bridge maintenance

**Introduction**

Sustainable development has been a focus of construction industry for the last two decades owing to issues of limited resources and climate change. Infrastructures like bridges, roads, railways and so on cannot be ruled out of such issues emerging from the amount of materials and resources they consume during their construction and maintenance life cycle phase (Pollalis et al., 2012). The local highway network includes over 50,000 bridges in the UK with a limited maintenance budget of £6 billion for 2015 to 2021 (DOT, 2013). Bridge maintenance is therefore a life cycle. However, it is worth investigating whether less maintenance schemes equals less environmental impact to decide a sustainable structural form. This emerges from increasing emphasis on environmental matters of climate change and limited resources (DECC, 2016). It is envisaged that a structural form with less environmental impact (i.e. consumes less resources, limited impact on climate change, consumes less energy and so on) from maintenance point of view could allow more sustainable bridges to be constructed.

**2. Literature review**

Sustainability of bridges has mostly been considered in terms of design, construction and material type (Du et al., 2014) but little attention has been given to sustainability of bridges from maintenance perspective. Sustainability in bridge maintenance is only starting to be explored for new construction through the application of Life-cycle Assessment (LCA) which is beginning to gain ground across the built environment to improve sustainability (Pang et al., 2015), but only to a limited extent to bridge maintenance. LCA can provide indicators for environmental impact (e.g. climate change, resource use, metal depletion, water consumption) arising from construction, maintenance. LCA indicators are currently widely considered in bridge design regarding bridge form (Horvath and Hendrickson, 1998; Itoh and Kitagawa, 2003; Gervásio and Da Silva, 2008; Hammervold et al. 2013; Du et al., 2014), materials (Keoleian et al. 2005; Lounis and Daigle 2007; Bouhaya et al. 2009) or components (Steele et al., 2003; Martin, 2004; Keoleian et al., 2005; Collings, 2006; Du and Karoumi, 2014), but are rarely considered for bridge maintenance decisions.

The majority of studies used assumed figures due to lack of data (Keolein et al., 2005). For example, Itoh and Kitagawa (2003) derived maintenance information from inspection manual, Du and Karoumi 2013; 2014) gathered information from the industry and literatures, while other studies assumed no maintenance (Bouhaya et al. 2009). Only few studies have considered maintenance options in detail. For example, Steele *et al*. (2003) compared concrete saddle construction with anchor bracing and found out that saddling had great impact due to structure closure and traffic diversion. Pang et al. (2015) compared strengthening options for steel, carbon fiber-reinforced polymer (CFRP) and prestressing tendons. No literature is however available for comparing maintenance options for concrete, steel and masonry bridges. The current study explores the life-cycle environmental impact for common maintenance actions for concrete, steel and masonry bridges with the help of LCA methodology and aims to identify the most sustainable structural form in terms of bridge maintenance.

**3. Methodology**

LCA is used to identify the environmental impact of commonly used concrete, steel and masonry bridge maintenance activities. LCA is rooted in ISO 14040 (2006) and ISO 14044 (2006) international standards and systematically follows the framework. A generic application of LCA involves an iterative process with four phases (as shown in Figure 1):

1. goal and scope definition
2. life-cycle inventory
3. life-cycle impact assessment
4. analysis.

Five maintenance methods were selected for each bridge type (listed in Table 1) based on three criteria used by Ashurst’s (1993), such as:

* effectiveness: essential maintenance activity for the overall safety and performance of the bridge
* cost: greater than £10,000
* time interval: greater than 10 years.

Preventative maintenance actions are considered in the current study, but have been included in other LCA studies, e.g. repainting (Horvath and Hendrickson, 1998), re-asphalting and replacing steel in parapets (Hammervold et al. 2013), resurfacing, and re-waterproofing (Collings, 2006).

Data required for the LCA analysis were sought from the literature which was consistent with previous LCA studies (Du and Karoumi, 2013; 2014; Pang et al., 2015). Literature sources where data had been derived are presented in Table 2. Data derived from the literature were verified by bridge designers and engineers to ascertain their reliability. The study involved an online survey that allowed data gathered from online sources to be agreed, disagreed with or alternative data suggested. Average Percent of Majority Opinions (APMO) used in similar expert related research (Cottam et al., 2004), was used to a nominal scale (yes or no response), where percentage of agreed and disagreed responses, including percentage of no responses is calculated to achieve a specific cut-off percentage to determine consensus. Consensus was reached on a statement or value when the percentage of “agreed” or “disagreed” value was higher than the APMO cut-off percentage (Kapoor, 1987). Cut-of-rate is determined by:

Where APMO did not provide clear consensus, the mean value was adopted (Cottam *et al*., 2004; Henning and Jordan, 2016). Participants were asked to supply alternative estimates for disagreed data that compromised APMO. The mean value of the suggested data was however taken as consensus (Field and Hole, 2003), as used by English and Kernan 1976; Grobbelaar, 2006; Henning and Jordan, 2016. The mean value is only considered accurate if the dataset was normally distributed, otherwise the median and mode of the distribution should be applied (Field and Hole, 2003). Statistical Package for Social Science (SPSS) 13 was used to identify the distribution of the collected data. Shapiro Wik significance value of 0.05 was used, as universally used for Normality test. The null hypothesis that the dataset was normally distributed is accepted or rejected if the mean of the distribution is greater or less than the Shapiro Wik significance value respectively. The mean however is still subject to error but the error can be minimized by calculating the standard deviations (Field and Hole, 2003). Standard deviation (SD) is used to assess the variation in a population and for a normal distribution (Grobbelaar, 2006), and allows the boundaries of the mean to be calculated, known as confidence intervals. A 95% or 99% confidence interval is statistically acceptable (Fellow and Liu, 2008). SPSS was used to calculate the mean, SD and confidence interval of suggested data and all agreed data are presented in Table 3, which were used as input data for the SimaPro LCA software to evaluate the environmental impact of selected maintenance activities.

***3.1 Goal and scope definition***

The first stage of LCA analysis is the goal and scope definition. The goal of the LCA study is to reveal the environmental impact of selected maintenance actions of concrete, steel and masonry bridges in terms of life cycle emission and energy consumption. The scope of the LCA study includes materials consumption, transportation, energy and resources associated with each maintenance activity. Materials accounted for in the LCA analysis are concrete of various grades, asphalt concrete, steel, and sand. Whilst transportation of all materials from factories to site was assumed, consumption of petrol, diesel, water, and electricity were modelled as a background system. Background and foreground systems are described by Clift et al. (1998) and are applicable to complex structures like bridges. While background system uses site-specific data, background system supplies the foreground system with the necessary material and energy required through a homogenous market where individual plant processes and operations are unidentifiable (Clift et al., 1998). Both processes from a system approach are reliable (Finnveden et al., 2009). Data for the foreground systems were derived from relevant literature sources and were verified by experts. Background data (on energy, plants and electricity) were derived from SimaPro data-set, gathered by SimaPro from across Europe, United States, and China. The Europe background data-set was used for the current study. System boundaries (illustrating the background and foreground system) for all selected maintenance methods are shown in Figure 2. All LCA studies were conducted based on a functional unit which allows a fair comparison between the systems under study (Heijungs and Guinée, 1994; Rebitzer et al., 2004; Finnveden et al., 2009). Functional units are best specified under foreground and background system (Clift et al. 1998), as has been applied in this study. Two common functional units have been applied in LCA studies for bridges, 1m2 of bridge deck (Collings 2006; Hammervold et al. 2009) and 1 m unit length of the bridge (Du and Karoumi, 2012). Steele et al. (2003) however suggests that the functional unit is best defined in terms of service life. Functional unit was therefore defined as **“**one square meter bridge deck area over a 120-year life span”in the current study, that was consistent with 120 years average design life of UK bridges (BS 5400, 1999).

***3.2 Life-cycle inventory***

The second stage of LCA analysis is the life-cycle inventory. Sources of input data used in the study are presented in Table 4. Calculating inventories of material, energy consumption and emission during transportation for selected maintenance actions allows potential environmental impact associated with each action to be identified. The following assumptions were made. Transportation of materials to site taken was assumed to be 16km which falls within the range of average transportation of materials in the UK (Zhang et al., 2011). Average fuel consumption was assumed to be 10 litre /100 km which has also been used by Pang et al*.* (2015).

***3.3 Life cycle impact assessment***

Life-cycle impact assessment is the third phase of an LCA study that identifies emission associated with the life-cycle inventory to be converted into damage indicators (Jolliet et al., 2003; Pennington et al., 2004). It identifies the environmental impact from emitted substances (e.g. CO2, CO, NOx, etc.) and resources (e.g. water and land use) (Finnveden et al*.,* 2009). Impact assessment is considered at two main points (midpoint and endpoint), at which classification and characterization are carried out. The output can also be normalised, grouped and weighed. For the current study the LCIA processes carried out are classification, characterization and normalization. Classification involves selecting relevant impact categories that are related to emitted substances and resource (otherwise known as environmental indicators). For the study CO2, NO2, SO2 and energy were considered as environmental indicators, as they are widely considered internationally (UN, 2015) and have also been used in other LCA studies on bridges (Itoh and Kitagawa 2003; Keolein et al., 2005; Collings 2006; Gervásio and da Silva, 2008). Suitable impact categories are those that relate to resource depletion, human health, and ecosystem (Consoli et al., 1993). Selected impact categories for the study are Terrestrial acidification (TA), freshwater eutrophication (FE), climate change (CC), ozone depletion (OD), photochemical oxidation formation (POF), fossil fuel depletion (FE), metal depletion (MD) and particulate matter (PMF). Characterisation of substances was conducted with the Recipe methodology within the SimaPro 8.0.4 version. Subsequent normalization revealed the size of the impact category on human health, ecosystem quality, and resources on the European scale. Note that, normalised points are dimensionless and are applied to for scoring purpose to enable comparison (Steele et al., 2003).

**4. LCA analysis**

Environmental assessment results for the combined maintenance methods for concrete, steel and masonry bridges are considered at midpoint, endpoint and in terms of models are presented in the following sub-sections.

***4.1 Midpoint analysis***

Eight environmental impact indicators have been selected for the midpoint analysis for the selected maintenance activities for concrete, steel and masonry bridges, as shown in Figure 3. Steel had a high relative impact on CC, OD, POF, PMF, TA, FE, MD and FD with a percentage of 46%, 42%, 45%, 49%, 48%, 49%,48% and 42% respectively. While concrete had a percentage of 41%, 44%, 41%, 41%. 41%, 41%. 41% and 42% across the same category. Meanwhile masonry had 13%. 14%, 14%, 10%, 11%, 10%, 11% and 16% across the same category. The result therefore indicate that steel and concrete maintenance had more impact across all uncertainty and limitations.

***4.2 Endpoint analysis***

The end-point result on damage to human health, ecosystem and resource for concrete, steel and masonry bridge maintenance actions - based on the European normalised scale – is presented in Figure 4. Damage to resources during maintenance, measured in surplus energy is shown to be greater for concrete and steel bridge maintenance has they both attained a normalised point of 3, compared to masonry which attained a normalised point of 0.6. Similarly, concrete and steel bridge maintenance had higher impact on human health with a normalised point of 1 and 1.2 respectively, compared to masonry bridge maintenance which attained a normalised point of 0.3 based on disability-adjusted life years (DALYs) scale. DALYs express the number of year life lost and the number of years lived disabled. Concrete and steel maintenance even though had less impact on ecosystem with a normalised point almost approaching 0.5, yet masonry had much less impact with a normalised point of 0.1 based on (PDF m2 year). PDF m2 year expresses the loss of species over a certain area and time duration, using the unit potentially disappeared fraction of species. The result characterisation and normalised result therefore indicate that masonry bridge maintenance activities is considerably less lower than concrete and steel bridges.

***4.3 Uncertainty and limitations***

Input data for the current LCA study were obtained from the literature, expert advice and SimaPro database. Assumptions were however made for input data that could not be easily accessed, such as average distance for transportation materials was assumed to be 16km for all maintenance activities and average fuel consumption was assumed to be 10 L/100 km for all vehicles. The assumed data will ensure fair comparison between selected maintenance methods but would be different for specific case studies. Maintenance was assumed to take place at scheduled intervals, however timing of maintenance activities varies for structures due to additional accidental damage or environmental impact. Specific case studies will also use local data instead of the European database available by SimaPro. Monte Carlo simulation was performed to identify for the variability of the input parameters and the environmental impact, associated with distance for transportation, frequency of maintenance activities, differences in fuel consumption and other input parameters. The SimaPro software allowed the Monte Carlo simulation at a statistical confidence interval of 95% to be carried out. A lognormal distribution was assumed for selected variables to allow the Monte Carlo simulation to identify the parameter with variation in respect to the result obtained in Figure 3 (i.e. characterisation result for compared maintenance methods of concrete, steel and masonry bridges). One thousand iterations were conducted based on previous studies (Parsons, 2016) and the output is shown for the Monte Carlo simulation comparing concrete and masonry bridge maintenance (Figure 5), masonry and steel bridge maintenance (Figure 6) and concrete and steel bridge maintenance (Figure 7) at characterisation level. No new result emerged from the simulation compared to results presented in Figure 3 and can be assumed that the uncertainty has limited impact on the test results.

**5. Discussion**

On the average, masonry bridge maintenance only accounted for 12% impact while concrete and steel bridge maintenance accounted for 42% and 46% impact. It therefore indicates that masonry bridges are 90% more sustainable from maintenance perspective. In support of this, literature reports that 40% of Surrey County bridge stocks undertook major refurbishment at an average age of 190 years into the service life. However, only masonry bridges exceeded current design life without significant repairs (Steele *et al*., 2002). In order to assess the sustainability of bridges over their life span, cradle to grave assessment has to be carried out to include raw material extraction, material processing, manufacturing, transportation, construction, preventative maintenance, disposal, recycling, etc. The actual service life also needs to be taken into consideration in the analysis. Although new bridges are designed for 120 years, most masonry bridges are well over 100 years and are expected to continue carrying traffic for the foreseeable future. In terms of new construction, masonry bridges are not considered as alternatives any longer and new bridges are generally limited to concrete, steel and composite structures (Collings, 2006). As the importance of sustainability is likely to increase in future, masonry bridges may attract more interest as a viable choice of bridge form.

**6. Conclusions**

A comparison of environmental impact of concrete, steel and masonry bridge maintenance activities was carried out in this study. The study considered preventive and corrective maintenance on the bases of effectiveness, cost and intervals. A life cycle assessment methodology was used to evaluate the environmental impact of selected maintenance action which accounted for associated material, energy and transportation used. Material quantities were derived from the literature and confirmed by industry experts as well as SimaPro data. Selected maintenance actions were evaluated on the basis of eight impact categories and the significance of their impact was based on human health, ecosystem and resources based on European scale.

Findings from the study has led to the conclusion that:

* Concrete and steel bridge maintenance activities have an average impact of 42% and 46% compared to 12% impact of masonry bridge maintenance. As such, the automatic preference for concrete and steel bridges should be reviewed.

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