Title: Sustainability of Bridge Maintenance

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Abstract

Bridge maintenance activities are important to consider within sustainable development due to the 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. Typical maintenance aspects of the predominant forms of bridge structure (i.e. concrete, steel and masonry bridge) were considered in this study to reveal their sustainability in terms of material, energy, transportation, human health and ecosystem. Results indicate that concrete and steel bridge maintenance activities have an average impact of 42% and 46% compared to 12% of masonry bridge maintenance activities. The paper concludes that the components parts of concrete and steel bridges should be revised as they play integral role in the selection of maintenance options.

Keywords

Bridge; sustainability; life cycle assessment; bridge maintenance

Introduction

Sustainable development has been a focus of the construction industry for the last two decades in order to address issues such as limited resources, environmental degradation and climate change. Transport infrastructure including bridges, roads and railways must be considered as central to sustainable development given the amount of material and energy resources they consume during their construction, maintenance and deconstruction life cycle phases (Pollalis et al., 2012). This emerges from increasing emphasis on environmental matters of climate change and limited resources (DECC, 2016). The UK local highway network includes over 50,000 bridges with a limited maintenance budget of £6 billion for 2015 to 2021 (DOT, 2013). Bridge maintenance is therefore subject to financial constraints during the bridge life cycle that may impact on their sustainability and it follows that the design of bridges should consider maintenance aspects in order to improve sustainability of the network. Therefore, it is worth investigating the environmental impact of the maintenance phase of different types of bridges to inform decisions about the most sustainable structural forms. It is envisaged that a structural form with lower 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 a maintenance perspective. Sustainability in bridge maintenance is only starting to be explored for new construction through the application of Life-cycle Assessment (LCA), a method which is beginning to gain ground across the built environment in order to improve sustainability (Pang et al., 2015). LCA can provide indicators for environmental impact (e.g. climate change, resource use, metal depletion, water consumption) arising from construction, maintenance and demolition/replacement. Literature reveals that, LCA indicators are currently 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 simple aggregated estimations of figures for bridge maintenance 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 literature, while other studies assumed no maintenance (Bouhaya et al. 2009). 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 greater impact due to structure closure and traffic diversion. Pang et al. (2015) compared strengthening options for steel, carbon fibre-reinforced polymer (CFRP) and prestressing tendons. No literature is however available for comparing maintenance options for concrete, steel and masonry bridges. Therefore this study will compare outputs for maintenance operation of typical bridge forms with the help of LCA methodology.

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 these frameworks . 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 (1993):

- effectiveness: the activity is an essential maintenance activity for the overall safety and performance of the bridge
- cost: the cost of the activity is greater than £10,000
- time interval: activities are typically carried out after intervals greater than 10 years.

Table 1 Selection criteria selected maintenance methods

Bridge Type	Maintenance Methods	Selection criteria			Source	Remarks
		Effectiveness	Cost	Intervals		
Concrete bridge	Grouting	- Used to fill crack holes and prevent collapse	- Slightly expensive - Estimated cost of £15,000	Every 30 years	(TAMP, 2005)	Less rigorous
	Overlaying	- Returns existing road surface to good condition	- More expensive - Estimated cost of £100,000	Every 30 years	(TAMP. 2005)	Very rigorous
	Deck replacement	- Restores totally damaged and deteriorated bridge	- Very expensive - Estimated cost of £622, 000	In 120 years	(TAMP. 2005)	Extremely rigorous
	Bearing renewal	- Ensures a serviceable limit state is maintained	- More expensive - Estimated cost of £60, 000	Every 30 years	(TAMP. 2005)	Less rigorous
	Expansion joint renewal	- Ensures a serviceable limit state is maintained	- Less expensive - Estimated cost of £15, 000	Every 20 years	(TAMP. 2005)	Less rigorous
Steel bridge	Structural metal painting	- Ensures physical defects like rusted parts are back to normal	- Less expensive - Estimated cost of £10,000	Every 12 years	(TAMP. 2005)	Less rigorous
	Deck re-waterproofing	- Provides adequate draining system for the bridge	- More expensive - Estimated cost of £30,000	Every 20 years	(TAMP. 2005)	Less rigorous
	Pavement repair	- Returns existing road surface to good condition	- More expensive - Estimated cost of £90,000	Every 30 years	(TAMP. 2005)	Slightly rigorous
	Bearing renewal	- Ensures a serviceable limit state is maintained	- More expensive - Estimated cost of £60, 000	Every 30 years	(TAMP. 2005)	Less rigorous
	Expansion joint renewal	- Ensures a serviceable limit state is maintained	- Less expensive - Estimated cost of £15, 000	Every 20 years	(TAMP. 2005)	Less rigorous
Masonry arch bridge	Saddling	- Able to solve multiple deterioration problems at once	- High cost amounting from material and labour intensity. - Estimated cost of £23400	Masonry bridge that have undergone this type of repair may not require such rehabilitation in 200 years	(Swoden, 1990; CIRIA, 2006; Parke and Hewson, 2008)	Rigorous work involved
	Radial pinning	- Able to strengthen the arch barrel	- less expensive - Estimated cost of £10, 000)	Masonry bridge that have undergone this type of repair may not require such rehabilitation work in 120 years	(Swoden, 1990; CIRIA, 2006; Parke and Hewson, 2008)	Less rigorous
	Water-proofing	- Provides a drainage system for the bridge.	- Slightly expensive. - Estimated cost of £10,000	May not be required till another 100 years	(Page, 1996)	Less rigorous
	Near surface reinforcement	- Strengthens the arch barrel by providing resistance across underneath cracked areas	- Slightly expensive. - Estimated cost of £11,000	May not be required till another 100 years	(Page, 1996)	Less rigorous
	Sprayed concrete	- Able to solve arch ring deterioration problems - Affects the final appearance of the bridge	- Slightly expensive - Estimated cost of £10,800	May not be required till another 100 years	(Swoden, 1990; CIRIA, 2006; Parke and Hewson, 2008)	Less rigorous

Preventative maintenance actions are considered in the current study, in line with related 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.

Table 2 Sources of extracted data

Year	Authors	Focused on	Criteria for selection
1993	Arshurst	Masonry bridge	Repair and maintenance techniques data
1996	Page	Masonry bridge	Repair and maintenance techniques data
1996	Horvath and Hendrickson	Concrete and steel	Environmental impact of construction materials
2003	Steele *et al*.	Masonry	Bridge repair and maintenance techniques data
2003	Collins	Concrete bridge	Environmental impact of Construction
2004	Sustainable bridges	Concrete, steel and masonry	Construction, maintenance, repair and rehabilitation techniques
2005	Steele *et al*.	Masonry bridges	Maintenance data
2005	TAMP	Concrete, steel and masonry bridge	Maintenance type
2006	Collins	Concrete, steel and concrete-steel composite	Environmental impact of Construction materials
2006	Guettala and Abibsi	Concrete bridge	Types deterioration and repair techniques
2008	Hammond and Jones	Construction materials	Embodied energy for construction materials
2010	Pacheco *et al*.	Steel bridge	Energy, transportation, manufacturing data
2011	Zhang *et al*.	Steel bridge	Construction and maintenance data
2012	Giutozzi *et al*.	Road pavement maintenance	Maintenance and transportation data
2012	Du	Railway bridges	Maintenance data
2013	Hammervold *et al*.	Steel, wooden and concrete	Construction and maintenance materials
2014	Du and Karoumi	Railway bridges	Construction and materials
2015	Pang *et al*.	Structural bridge maintenance	Maintenance material
2016	Sarhosis *et al*.	Masonry bridge	Maintenance material

Data derived from the literature were verified by 57 industry expert, comprising of (37) bridge engineer, (10) bridge manager and (10) design managers to ascertain their reliability. The verification process involved an online survey which allowed these experts to agree, disagree or suggest alternative data. 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) to determine a cut-off percentage. 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-off-rate is determined by equation 1:

$$\mathbf{APMO} = \frac{\text{Majority Agreements} + \text{Majority Disagreements}}{\text{S of Opinions expressed}} \tag{1}$$

S is the sum of opinions expressed, either in agreement or disagreement with the literature data. Majority agreement, is the total number of opinions in agreement with the literature data, whiles majority disagreement, is the total number of opinions in disagreement with the literature data. 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 data that they disagreed with. The mean value of the suggested data was taken as consensus for statements that were widely disagreed with or on which there was no 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 a dataset is normally distributed, otherwise the median or mode of the distribution should be applied (Field and Hole, 2003). Statistical Package for Social Science (SPSS) 13 was used to test the normality of the collected data. Shapiro Wik significance value of 0.05 was used and the data was found to conform to the normal distribution. 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 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.

Table 3 Agreed and verified material quantities

Structural type	Maintenance activities	Materials	Quantities of materials (tons/sq.m)	Quantities of materials (Kg)
Concrete bridge	Grouting	Cementitious grout	.14	140
	Overlaying	Concrete	.22	220
		Asphalt	.27	270
		Bitumen	.3	300
	Bearing renewal	Reinforcement	.25	250
	Expansion joint renewal	Reinforcement	.25	250
	Deck replacement	Concrete	2.5	2500
		Asphalt	.27	270
		Reinforcement	.12	120
		Bitumen	.3	300
Steel bridge	Structural painting	Epoxy paint	.00051	.051
		Polyurethane paint	.000103	.103
		Zinc coating	.0004	.4
	Pavement repair	Asphalt	.27	270
		Bitumen	.3	300
	Deck re-waterproofing	Concrete	.1	100
		Reinforcement	.1	100
	Bearing renewal	Reinforcement	.25	250
	Expansion joint renewal	Reinforcement	.25	250
Masonry arch bridge	Saddling	Concrete	2.5	2500
		Asphalt	.27	270
		Reinforcement	.25	250
		Bitumen	.3	300
		Fill	2	2000
	Radial pining	Cementitious grout	.12	120
		Dowel reinforcement	.12	120
	Waterproofing	Concrete	.1	100
		Asphalt	.1	100
		Mastic seal	.1	100
	Near-surface reinforcement	Cementitious grout	.152	152
		Reinforcement	.203	203
	Sprayed concrete	Concrete	.4	400
		Reinforcement mesh	.1	100

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, 1m^2 of bridge deck (Collings 2006; Hammervold et al. 2009) and 1m 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" 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 2 and 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).

Table 4 Origin of inventory data

Life cycle stage	Sub process	Data origin
Maintenance	Cementitious grout	Literature
	C30 and C40 Concrete	Literature
	Asphalt	Literature
	Bitumen	Literature
	Reinforcement	Literature
	Epoxy paint	Literature
	Polyurethane paint	Literature
	Zinc coating	Literature
	Reinforcement mesh	Literature
	Mastic seal	Literature
	Production of electricity, diesel, and gasoline	SimaPro
	Combustion of electricity, diesel and gasoline	SimaPro
	Production of water	SimaPro
	Energy resources	SimaPro

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. CO_2, 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 weighted. 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 CO_2, NO_2, SO_2 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 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 selected indicators.

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. The European normalised scale is measured by (damage to resources, DALY and PDF m^2 year). 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 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 m^2 year). PDF m^2 year expresses the loss of species over a certain area and time duration, using the unit potentially disappeared fraction of species. The overarching results therefore proofs that masonry bridge is better on all measures.

4.3 Uncertainty and limitations

Input data for the current LCA study were obtained from the literature, expert advice and SimaPro (an up-to-date LCA software). 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 account for the variability of 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 therefore it can be assumed that the uncertainty has limited impact on the test results.

5. Discussion

The LCA outcome provides a useful insight to the impact of certain typical maintenance aspects of the predominant forms of bridge structure. On the average, masonry bridge maintenance only accounted for 12% impact while concrete and steel bridge maintenance accounted for 42% and 46% impact. Results therefore indicates that, maintenance actions for masonry bridges are more environmentally sustainable. 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. The results also suggest that specific components parts of concrete and steel bridges could to be revised as they attract more impactful maintenance options. For example, maintenance of expansion joint had the highest impact on CO_2, NO_2, and SO_2 emission (see supplementary data).

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 and combined with 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 were 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 may need to be reviewed. Furthermore, designers should consider revising the components parts of concrete and steel bridges as they play a critical role in the selection of maintenance options which influence the degree of impact.

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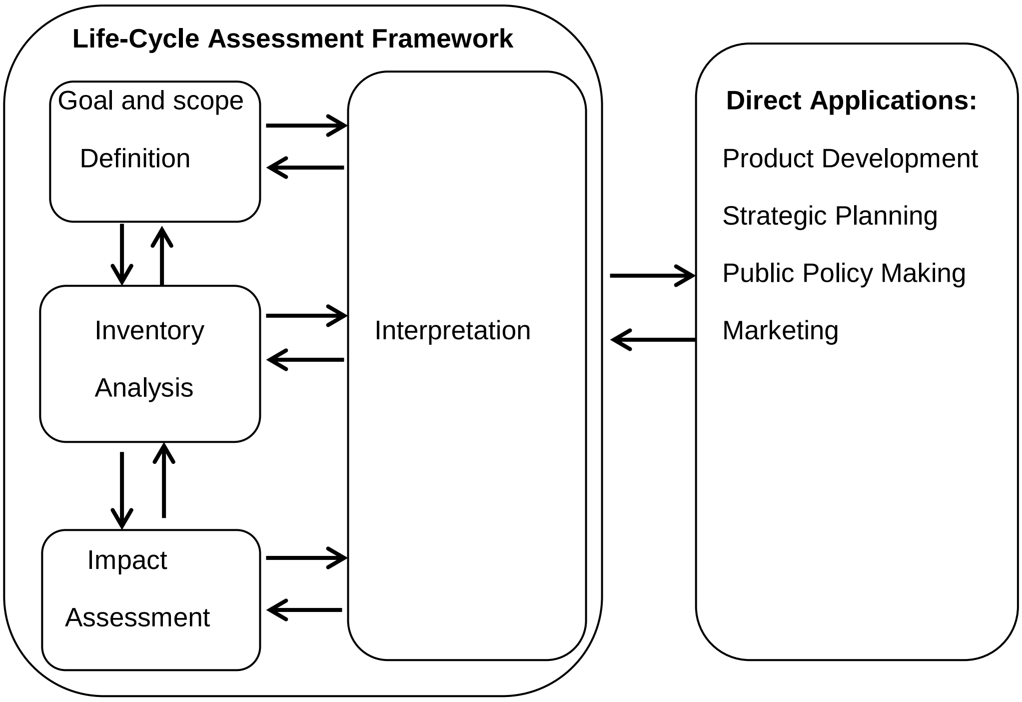

Figure 1 Life-cycle assessment Framework. *source:* Adapted from ISO 14040 (2006)

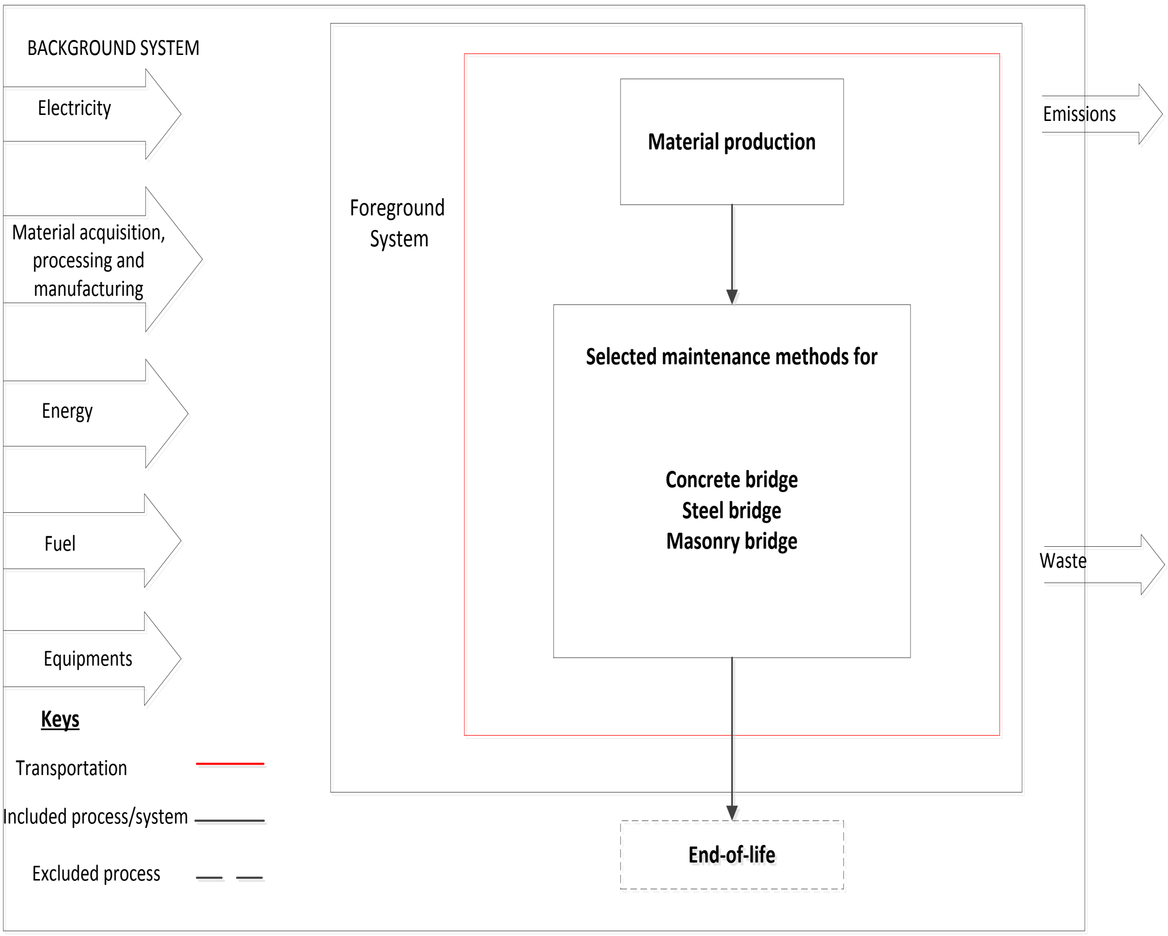

Figure 2 System boundary for maintenance work

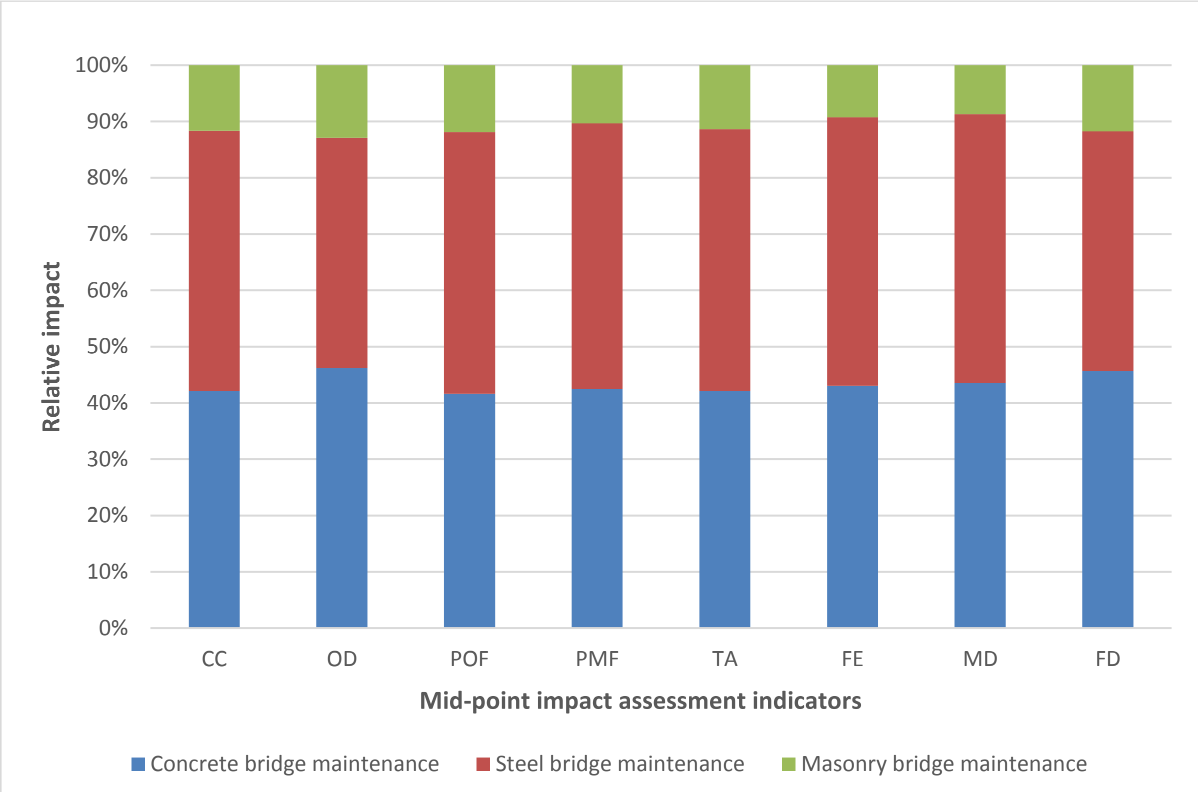

Figure 3 Characterization results for combined *maintenance methods of concrete, steel and masonry bridge*

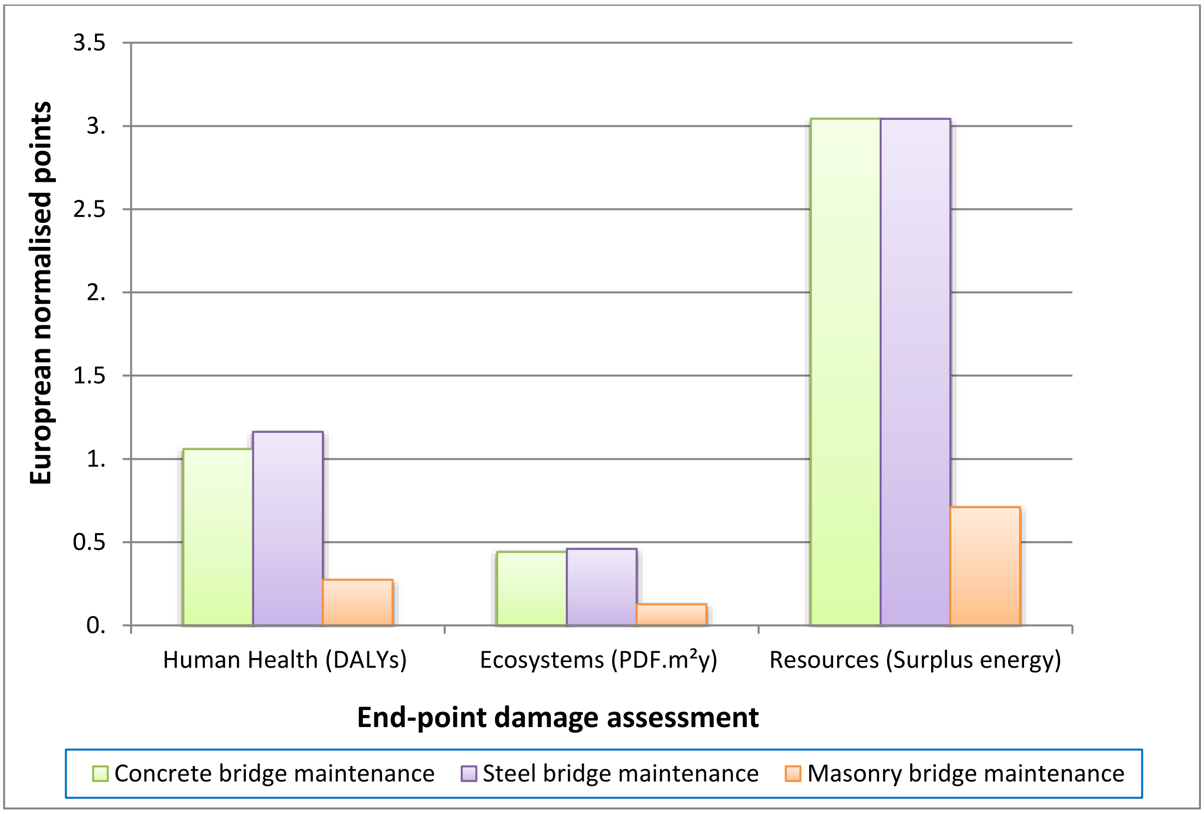

Figure 4 Normalised results of concrete, steel and masonry bridge maintenance methods on European scale

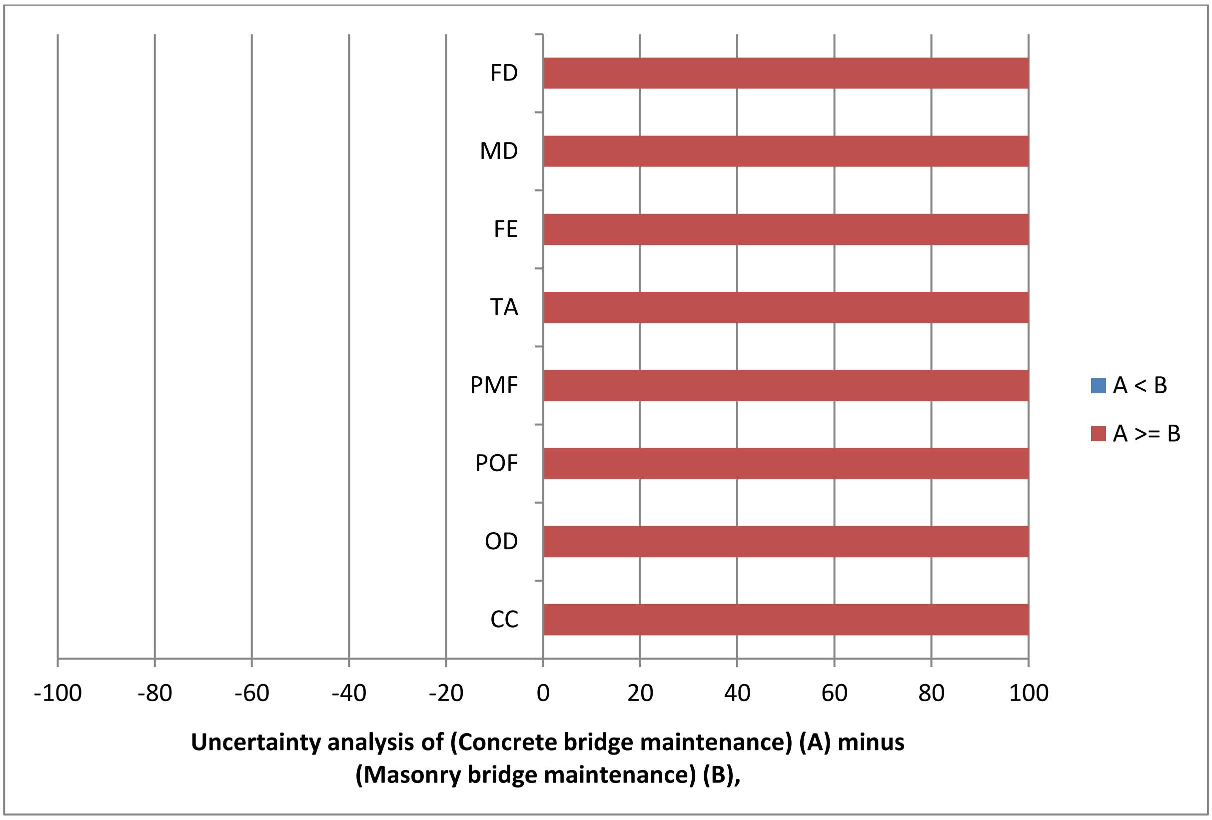

Figure 5 Uncertainty analysis for compared concrete and masonry bridge maintenance

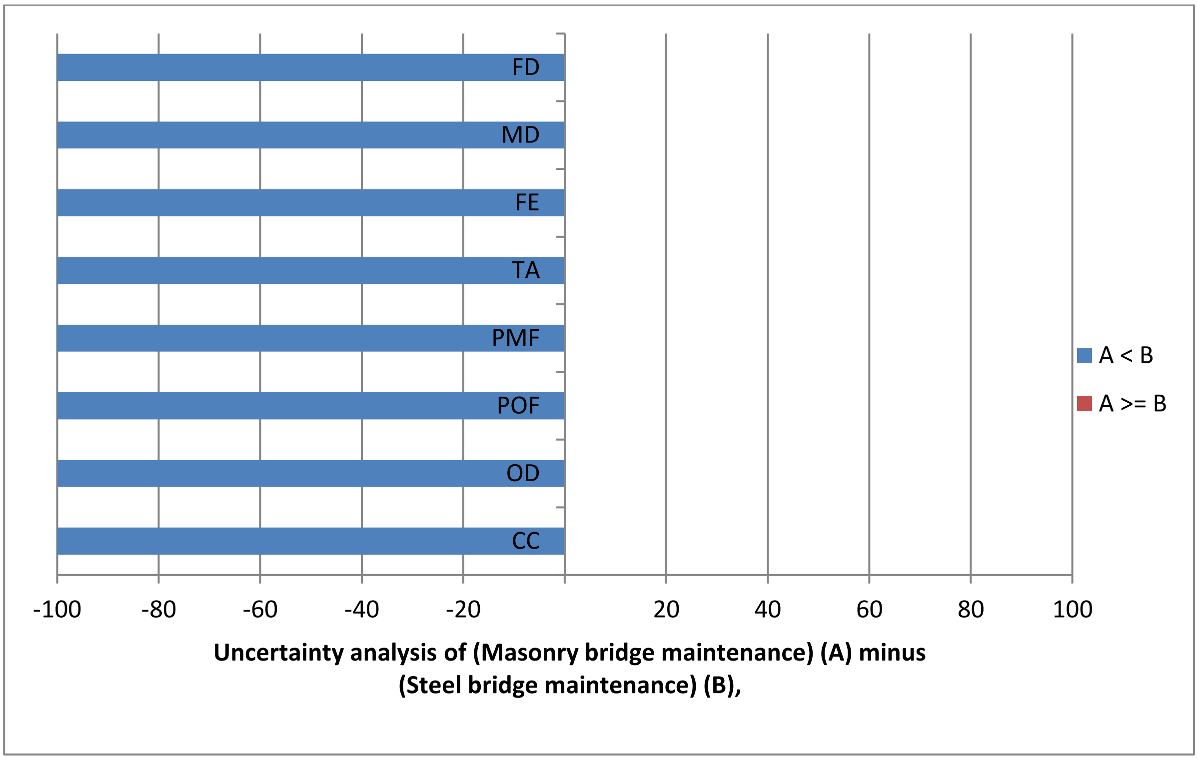

Figure 6 Uncertainty analysis for compared steel and masonry bridge maintenance

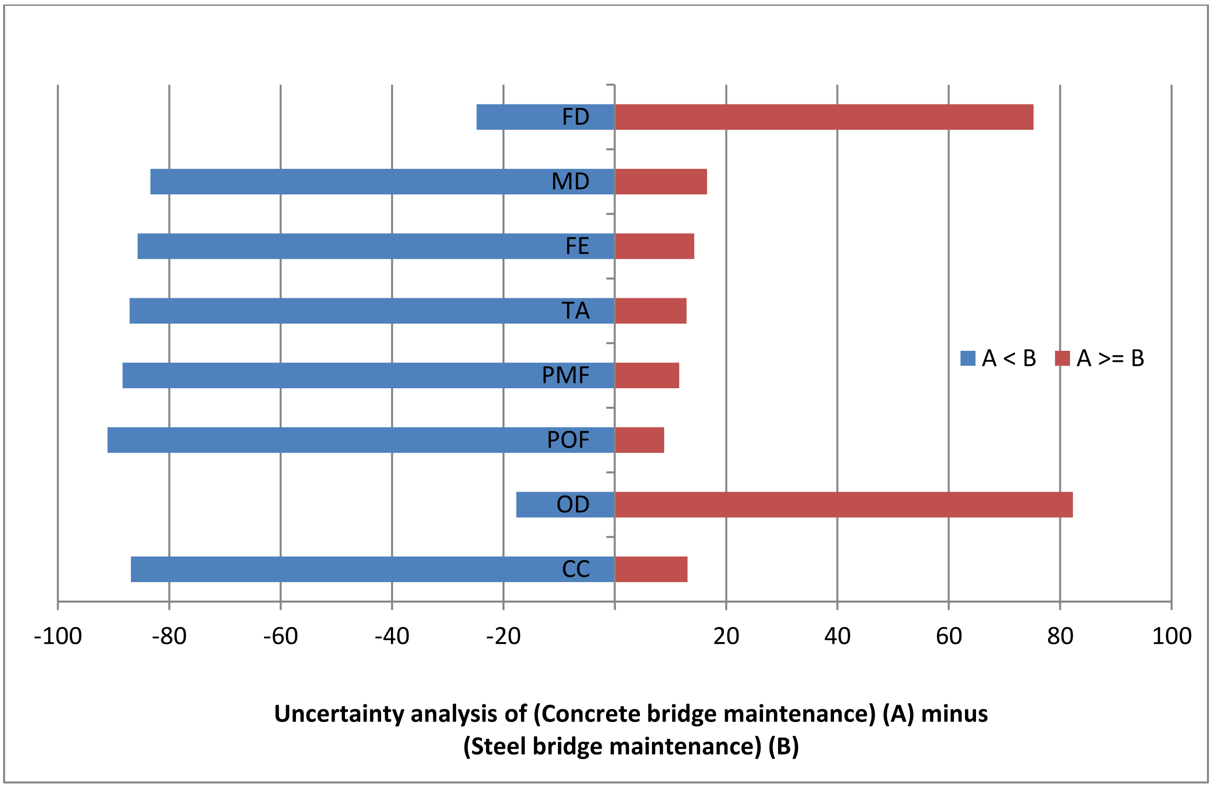

Figure 7 Uncertainty analysis for compared concrete and steel bridge maintenance