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# Life-cycle assessment environmental sustainability in bridge design and maintenance

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**Title: LCA Environmental Sustainability in Bridge Design and Maintenance**

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## **Abstract**

Environmental sustainability issues are being considered across many construction sectors, emerging from global concerns on resource depletion and CO<sub>2</sub> emissions from activities in the sector. Whilst construction sectors are addressing the environmental impact of their activities at the construction stage and the associated CO<sub>2</sub> and GHG emissions, LCA (Life Cycle Assessment-an environmental tool) is not being fully factored into the early design stage of bridges to facilitate design choices. Face-to-face and in-depth semi-structured interviews were employed in this study, to reveal experts' opinion on environmental considerations in bridge design and possibilities of integrating LCA in this process. Findings revealed that LCA incorporation into the design process will be a complex matter, as the design process is already intricate, and need for the bridge, access to future maintenance, use of quality materials, longevity and cost savings are more sustainability matters taken seriously, compared to life cycle environmental emissions. Moreover, the paucity of LCA awareness amongst bridge designers, along with keenness to execute clients' requirement, mostly cost driven, further widens the gap. This study, therefore, provides four recommendations to bridge the identified gap: (1) detailed environmental matters such as CO<sub>2</sub>, NO<sub>2</sub> and GHG emissions should be considered as design criteria; (2) encourage designers to highlight emerging environmental matters in the design brief; (3) LCA awareness should be heightened amongst bridge designers to increase potential usage; and (4) LCA damage indicators may be factored into the bridge design process.

## **Keywords**

Bridge; sustainability; life cycle assessment; bridge maintenance; bridge design; environmental impact

## 1 **Introduction**

2 Bridges are an integral part of the road and rail network, playing a vital role in economic  
3 development and allowing the transportation of goods and services from one place to another  
4 (Wilmers, 2012). Sustainability in bridge design has started gaining interest, stemming from the  
5 role of design in achieving overarching sustainable development targets (DBERR, 2008) and  
6 from the fact that decisions made in the early design process have far reaching environmental  
7 impact (Riches, 2003; Collings, 2006; Ainger and Fenner, 2014). More so, a sustainable design  
8 is that which contributes to the triple bottom lines of environmental, social and economic  
9 sustainability (DBERR, 2008). Not many researches have considered environmental  
10 sustainability of bridges (Arya et al., 2015), especially from a life cycle assessment view point,  
11 considering the fact that the design process itself is largely dominated by technical and safety  
12 issues, with limited attention paid towards environmental matters (Du and Karoumi 2014).  
13 However, built environment sectors are now largely considering LCA approach to minimise  
14 environmental pollution in their activities (Cabeza et al., 2014). LCA results present  
15 environmental indicators such as climate change, resource use and depletion, water  
16 consumption and so on, which are rarely considered at the early design stage of bridges. These  
17 indicators are now part of urgent sustainable development matters in Agenda 2030 (United  
18 Nations, 2015), and will need to be considered for bridges. This paper presents a review of  
19 available literature, case studies and synthesis of case studies in the domain of LCA application  
20 to bridges and employs a qualitative approach (semi-structured interview) to explore experts'  
21 perspectives on environmental sustainability of bridges and understand their views on  
22 incorporating LCA in bridge design. The results drawn from the interviews were used to provide  
23 recommendations to bridge the gap between the current perception of environmental  
24 sustainability in bridges and the application of LCA in this concept.

## 25 **2. A Review of LCA application to bridges**

26 LCA is a quantitative method developed to calculate the life cycle environmental impacts of  
27 product design (Ainger and Fenner, 2014). Although it can be applied to complex structures like  
28 bridges (Du and Karoumi, 2013), only limited literature is available on LCA of bridges (Keoleian  
29 et al., 2005), including highways, railways, and waterways. Authors like Huang, et al. (2009) and

30 Santero, et al. (2011) have worked on LCA of asphalt pavement. Table 1 presents an overview  
31 of review papers published within the last 8 years on buildings, roads and bridges, and of the  
32 papers reviewed, only one was specific to bridges. Bridge LCA has mainly been used for  
33 comparison purposes (i.e. comparing different bridge forms, materials, components, and design  
34 elements). However, only a small body of literature has compared bridge maintenance methods  
35 (Steele et al., 2003; Pang et al., 2015, Balogun et al., 2018), though none has considered  
36 experts' opinion on incorporating the tool itself into bridge design, as presented in this study.  
37 Table 2 presents case studies comparing bridge forms, elements, components, materials and  
38 design using LCA methodologies. It was evident that only the superstructure (deck component)  
39 of the bridge was accounted for, mostly, and only a handful considered sub-structural  
40 components. Impact assessments principally considered are CO<sub>2</sub> emissions and energy with  
41 depletion of abiotic resources, acidification, eutrophication, climate change, ozone layer  
42 depletion, and photo-oxidant creation, and possibly an attempt to contribute to the on-going  
43 global debate. Generally, it can be inferred that results were largely determined by the input  
44 parameters of Life Cycle Inventories (LCI), system boundaries and impact assessment  
45 methodologies adopted. Therefore, even the same bridge under a different scenario can yield a  
46 different result, more so as there is a high level of uncertainty about the data collected. Although  
47 Zhang, Wu and Wang (2016) tried to address uncertainty issues in LCA of bridges through  
48 sensitivity analysis, it does not change the fact that data availability is the root cause for most  
49 uncertainty problems in bridge LCA studies and perhaps justifies the need for experts to validate  
50 the practical relevance of the outcome. Similarly, only issues of uncertainties, functional units,  
51 data availability, system boundaries, methodology and impact assessment categories have  
52 been addressed (Crawford 2011; Du and Karoumi 2014; Panesar, et al., 2017) and limited  
53 attention paid towards how interpreted results will support decision making, considering that  
54 many of these results are subject to the shortcomings. Du et al. (2014), for example, struggled  
55 to reach a convincing conclusion and asserted that only a comprehensive LCA that considers all  
56 impact categories could allow a detailed conclusion to be reached. More so, the choice of what  
57 to include in the analysis depends solely on the investigator (Crawford, 2011; Du et al., 2014;  
58 Pang et al., 2015). According to Cowell (1998), the usefulness of LCA results is measured  
59 through four criteria: accuracy, relevance, comprehensibility, meaningfulness, and acceptability

60 as a legitimate form of analysis. While these criteria are vaguely considered, stakeholder  
61 engagement can help the researcher understand this matter a lot more (Shiels, 2005; Selmes,  
62 2005; Sala, et al, 2013). None of the case studies presented the usefulness of the result through  
63 a structured approach. Exploring the usefulness of bridge LCA results will potentially aid  
64 practical implementation and wider applicability of LCA, considering that its application is still  
65 limited in the bridge industry. The limited application can be traced to a lack of knowledge and  
66 awareness (Tan, et al., 1999; Crawford, 2011), and possibly doubts regarding the integrity of the  
67 results. However, to fully understand environmental sustainability and the integration of LCA tool  
68 in the bridge design process, the following questions need to be addressed:

- 69 1. Which environmental sustainability criteria are factored into new bridge design?
- 70 2. What are the drivers of structural or maintenance solutions?
- 71 3. What is the degree of LCA awareness amongst bridge designers?

### 72 **3. Methodology**

73 Given the need to identify expert opinion on the usefulness of LCA in bridge design, in-depth  
74 semi-structured interviews were conducted with 21 industry experts identified through a snow  
75 ball sampling strategy. Interviewees included nine bridge designers, eight bridge engineers, one  
76 design manager, one renewal engineer and one asset engineer. Interviewees spanned the  
77 range of major bridge owners, clients, contractors, and consultants in the UK bridge industry.  
78 The background of participants in the study is presented in Table 3. Selection criteria for  
79 interviewees are as follows: minimum 15 years of work experience and a university degree.  
80 Interviewees were allowed to develop their own story and all interviews were recorded and  
81 transcribed as a Microsoft Word document. The transcribed document was read severally,  
82 edited, and organised into a suitable format before being fed into NVivo 11 (a qualitative data  
83 analysis software package) for analysis. Coding in NVivo package is used to store important  
84 extracts from the transcript and there two main types, selective coding and complete coding.  
85 Selective coding is a deliberate selection of instances relating to the phenomena of interest and  
86 requires pre-existing theoretical and analytical knowledge of the phenomena of interest (Braun  
87 and Clarke, 2013). Complete coding, on the other hand, does not look for particular instances  
88 within the dataset, but aims to identify anything and everything of interest or relevance to the

89 research question (Saunders et al, 2012). In line with this, the paper opted for complete coding  
90 and captured any relevant information useful for answering the research question. As such,  
91 phrases and words identified to provide answers to research questions one, two and three were  
92 coded accordingly. Developing themes involves a thorough review of similar codes with the  
93 hope of identifying similarities and overlap between them (Braun and Clarke, 2013). Identifying  
94 themes allows concepts and issues with similar focus to be gathered under a central organising  
95 concept. Therefore, a theme can capture vital information about the data in relation to the  
96 research question (Bazeley, 2013). On this account, the codes identified were sorted into  
97 potential themes. According to Braun and Clarke, (2013) themes appear on three main levels.

98 These are as follows:

- 99 • **Overarching Themes** do not contain codes or data, but capture an idea embedded in  
100 many themes;
- 101 • **Themes** themselves may or may not include sub-themes;
- 102 • **Sub-themes** capture relevant and specific aspects of the central organising concepts  
103 that contribute towards a particular theme.

104 Data were coded based on research questions one, two and three. This potentially allowed  
105 three different areas to be identified for initial coding: firstly, bridge designers' views on  
106 sustainability issues factored into new bridge design; secondly, drivers of design solutions for  
107 structural or maintenance work; and lastly, experts' opinion on the awareness and knowledge of  
108 LCA. Other themes and sub-themes emerged from further coding in relation to the overarching  
109 themes of the analysis. The thematic analysis employed in this study was underpinned by the  
110 researcher's theoretical and analytical interest (Boyatzis, 1998); as such, identified themes were  
111 not based on theory, but had the potential to address the research questions. Table 4 reveals a  
112 thematic map showing overarching theme, major themes and sub-themes derived from the  
113 research questions. For example, sustainability is embedded in three areas: in bridges,  
114 environmental considerations and environmental indicators. Emergent findings across the data  
115 (themes and sub-themes) were derived using the matrix coding query function in NVivo 11 and  
116 key extracts from interviews are presented in section 4).

117

## 118 4. Results and Discussion

119 Findings derived from the interview analysis are discussed under the three main research  
120 questions and compared with existing literature.

### 121 **4.1 Which sustainability criteria are factored into new bridge design?**

122 Interviews with experts revealed five areas (depicted in Figure 1) where sustainability is  
123 appraised in bridge design. Unfortunately, sustainability issues go beyond these areas, as  
124 elements of the triple bottom-line approach (environmental, economic, and social) need to be  
125 fully incorporated. For instance, cost, programme, aesthetics, constructability, health and safety,  
126 maintainability, environmental issues and so on need to be considered (Collings, 2006). At this  
127 time, predominant issues identified in the interviews as revealed in Figure 1, cover only  
128 economic and social aspects in some way, but not environment. Zhang (2010) equally agrees  
129 with these issues, yet, there is need to consider more environmental matters, as other  
130 sustainability elements depend on it to thrive (Selmes, 2005; Ainger and Fenner, 2014). In fact,  
131 Interviewee (N) informs that sustainability in bridge design is considered from the aspect of  
132 access to future maintenance and interviewee (E), states, '*... So you design a bridge in such a*  
133 *way that you can get to the bearing to take out the existing bearing and replace with new one,*  
134 *whether you think they are going to need replacement or not, you always make provisions, so*  
135 *they can be done.*' Moreover, attention is increasingly being drawn to environmental matters  
136 stemming from the risk and uncertainty of resource depletion, CO<sub>2</sub> emissions and other Green  
137 House Gas (GHG) matters (UN, 2015). Interviewee (D) made an interesting point that  
138 environmental sustainability in bridges can be a casualty, if cost is the motivating factor.  
139 Interviewee (D) expressed, '*... You could have several structural engineers designing bridge*  
140 *works to minimise carbon foot print; but then the people who undertake the work who source the*  
141 *material could undermine it by bringing materials from overseas with all the transportation cost*  
142 *because it works out cheap for them*'  
143 Moreover, interviewees revealed that protection of flora, fauna, surrounding environment and  
144 watercourses are the only sustainability considerations accorded to bridge maintenance works,  
145 although these checks are a statutory EIA requirement, and align with Yeang's (2010)

146 recommendation for achieving a green built environment. According to Interviewee D, '*... It has*  
147 *always been about avoiding any harmful material from getting into the watercourses, avoiding*  
148 *salt being kicked up into watercourse, avoid disturbing the flora and fauna in or around the*  
149 *watercourse and that's always been the main environmental drive.'* Environmental emissions  
150 (such as CO<sub>2</sub>, NO<sub>2</sub>, SO<sub>2</sub> and so on) from the actual maintenance work are still being neglected.  
151 The bridge industry, however, needs to shift from the traditional cost driven approach and  
152 embrace a more environmentally- friendly approach, especially at the design stage, where every  
153 choice will affect the long-term sustainability performance of the bridge.

#### 154 **4.2 What are the drivers of structural or maintenance solutions?**

155 Interviewees revealed that clients are the major determinants of structural choices, and their  
156 choices are based on construction cost and long-term maintenance cost. According to  
157 Interviewee I, '*sustainability is one of those tick box exercises to say yes, we are*  
158 *environmentally friendly all those kind of stuff, but it depends on how you define sustainability,*  
159 *you want a structure which has long life which is 120 years with little amendments.'* It follows  
160 that designers need to suggest and justify sustainable options to clients. Suggestions can be  
161 accepted or rejected depending on the depth of justification (Wessels, 2014). Assessments  
162 such as CEEQUAL are developed to facilitate such justification and reward projects that  
163 demonstrate detailed sustainability considerations (CEEQUAL, 2017). Apart from the areas  
164 revealed in Figure 1, nine other drivers are revealed in Figure 2 (from the interview), which  
165 determine the choice of bridge maintenance actions. These drivers take precedence before any  
166 environmental matter is considered. While Interviewee L stated, '*... When we have a*  
167 *programme of work to do, how we go about that and the choice we make is influenced by –*  
168 *does that affect our funding or not, if it doesn't affect our funding, we do it as we've always done*  
169 *it. If it starts to affect or reduce our funding or gives us the need to increase our funding then we*  
170 *change the way we work, it is as simple as that really...*' Interviewee N agrees: '*... the drive is to*  
171 *apply certified quality material which will provide functionality and durability for the design life*  
172 *which itself it's a prerequisite so you don't have to build the thing again in 20 years' time...*'  
173 However, interviewee L feels, '*... Sustainability is a big issue at the moment and is a key factor*  
174 *when designing new structures in terms of environmental impact assessment. If you can prove*

175 *that your option is low or less impactful, then it would certainly be favourable by funding*  
176 *authorities. May be cost a little bit more but being a greener structure, that would help because*  
177 *cost these days doesn't mean we shouldn't be skimping out and creating problems latter on' .*  
178 As such, LCA may soon be an essential part of the decision-making process, as funding bodies  
179 are beginning to reward projects that demonstrate substantial environmental life cycle  
180 performance in terms of emissions. As environmental concerns are increasingly becoming a  
181 global concern and need to be considered in structural and maintenance solutions, designers  
182 may need to advise clients on issues of resource depletion, energy use, and CO<sub>2</sub> emissions at  
183 the early design stage or maintenance phase in line with their choice, with reasonable  
184 justifications. Otherwise, bridge designers will struggle to consider detailed environmental  
185 issues in their design. Materials and methodologies that lead towards minimal maintenance are  
186 also considered in design and maintenance choices. The use of alternative methods and  
187 materials to address environmental issues in bridges aligns with Zhang (2010). However, client  
188 choices and the designers' justifications play a major role in making these decisions.

#### 189 **4.3 What is the degree of LCA awareness amongst bridge designers?**

190 Interviews revealed that LCA awareness is limited amongst bridge engineers, let alone its  
191 usage. This was obvious from the interview conversations, as little interest was shown in the  
192 LCA methodology. Interviewee D reveals, '*... There is a life cycle assessment done but not*  
193 *formally with decision making about what route you are taking. I haven't come across a life cycle*  
194 *assessment where it is taken into account how much CO<sub>2</sub> is gonna be used for construction or*  
195 *during a planned maintenance. If that makes sense, so it doesn't really come into it'.* Moreover,  
196 interviewee (L) explains that the environmental effect of bridge maintenance can be negligible,  
197 in the sense that only a small portion of the bridge needs to be replaced with like-for-like parts,  
198 which may not necessarily require environmental assessment. Interviewee (E) highlights – '*In*  
199 *terms of maintenance, we don't think a lot about environmental effect, but we do try and think*  
200 *and make things that can be maintained.'* On the other hand, interviewee (K) argues that major  
201 clients largely consider life cycle issues during decision-making (e.g., whole life cost; life cycle  
202 cost; etc.). Interviewee (K) reveals that, '*... If we decide to replace it, part of our renewals team,*  
203 *we pass the bridge onto effectively program manage all of the replacement works, but part of*

204 *their scope and tender submission or things like that would have life cycle cost within it, life*  
205 *cycle maintenance and all that kind of stuff within it and helps us decide what the best option is.'*  
206 Experts claimed that LCA midpoint indicators were too complex to be incorporated into the  
207 design process. However, there could be room to incorporate the endpoint indicators. LCA was  
208 considered for only new constructions, if at all, but never for existing bridge maintenance work.  
209 According to Pang et al. (2015), LCA for bridge maintenance action is limited. However, failure  
210 to consider LCA for bridge maintenance action could impinge upon UK's effort to reduce CO<sub>2</sub>  
211 emissions by 2050. This stems from the fact that maintenance actions improve the serviceability  
212 and longevity of bridges, and require substantial material consumption (over a life span), with  
213 the relative impact on the environment. More so, maintenance output accounts for the highest  
214 value amongst the UK component parts (year in year out) (ONS, 2013, 2014, 2015, 2018), and  
215 should be taken seriously. The reality, however, is that design-maintenance process is already a  
216 complex one (Riches, 2003), and incorporation of LCA methodology could compound the  
217 complexity, even though the environmental indicators offered through LCA are becoming  
218 important sustainability matters (UN, 2015). The interviews revealed that there may be scope to  
219 include the damage indicators (that is resource depletion, ecosystem, and human health) of  
220 LCA in bridge design, even as the desire to factor environmental considerations into bridge  
221 design is growing (Du et al., 2014). LCA however is mainly suited to a definite system, which  
222 requires components, process, and material data to be precise (Millet et al., 2007).  
223 Unfortunately, precise data for bridges are scarce, and estimates and assumptions will need to  
224 be made (Du and Karoumi, 2014; Hammervold et al., 2013).

## 225 **5. Development of recommendations**

226 Deductions from the above discussions will underpin the development of recommendations for  
227 integrating LCA into bridge design and maintenance. The first deduction emerging from the  
228 findings attributed to question one, which informs that bridge designers can suggest the  
229 considerations of more environmental indicators such as resource depletion, energy, CO<sub>2</sub> and  
230 so on to clients, as the least they could do to influence sustainable decisions. However, this will  
231 require appropriate justification in the design brief. LCA becomes a useful tool in this regard. A  
232 second deduction also emerged from findings attributed to question one. This revealed that

233 sustainability is still a tick box exercise in the bridge industry and that vital environmental  
234 concerns such as CO<sub>2</sub>, NO<sub>2</sub>, and other GHG emissions are neglected in bridge maintenance  
235 work. Rather, protection of flora, fauna, environment and watercourses are more significant  
236 concerns. However, environmental issues of CO<sub>2</sub>, NO<sub>2</sub>, and other GHG emissions are  
237 becoming more pressing environmental concerns and should be factored into bridge  
238 maintenance operations, in adherence to UK's Climate Change Act, associated carbon  
239 emissions commitment and legal obligations placed on the infrastructural sector. LCA could be  
240 applied to achieve this purpose based on previous studies. Further, CO<sub>2</sub>, NO<sub>2</sub>, and other GHG  
241 emissions associated with maintenance work can be revealed and the result can guide  
242 sustainable maintenance and design choices.

243 The third and fourth deductions flowing from the findings relate to question three. Findings  
244 revealed that LCA awareness is limited amongst bridge engineers, let alone its usage.  
245 Facilitating awareness and benefits of LCA amongst bridge designers is therefore the key.  
246 Again, LCA awareness will be unproductive if environmental matters are not significantly  
247 considered as design criteria. Largely, many of the interviewees revealed that environmental  
248 emissions are not necessarily a design criterion compared to cost, programme, aesthetics,  
249 constructability, health and safety, and maintainability. LCA awareness can gain greater  
250 momentum amongst bridge designers, should relevant environmental matters be formally  
251 considered as a design criterion. Further, a fourth deduction emerges from the fact that there is  
252 scope to integrate only the damage indicators (with other design criteria) in bridge design.  
253 Incorporation of the damage indicators alone will perhaps reduce the complexity of embedding  
254 the entire LCA process in bridge design. The question now is how flexible can the LCA be,  
255 before it is no longer an LCA. While addressing the complexity of LCA in bridge design, the  
256 process itself should not be undermined, in that the damage indicators themselves are outputs  
257 from the whole LCA process.

258 A set of recommendations have emerged from the deductions presented. Recommendations  
259 will pave the way for general integration of LCA into bridge design. These recommendations can  
260 help the bridge industry contribute towards the environmental sustainability development goal  
261 relating to the overall built environment. Providing recommendations towards the improvement  
262 of environmental sustainability practices in the built environment sector is not unusual (CIRIA,

263 2006). However, recommendations derived from expert input through semi-structured interviews  
264 are not yet available to the UK bridge industry. Although Zhang (2010) presented some  
265 recommendations to help bridge designers improve practice and contribute towards CO<sub>2</sub>  
266 reduction, they did not consider expert input. The recommendations presented in this study are  
267 as follows:

- 268 1. Detailed environmental matters such as CO<sub>2</sub>, NO<sub>2</sub> and GHG emissions should be  
269 considered as design criteria;
- 270 2. Designers should be encouraged to highlight emerging environmental matters in the  
271 design brief; (3)
- 272 3. LCA awareness should be heightened amongst bridge designers to increase potential  
273 usage; and
- 274 4. LCA damage indicators may be factored into the bridge design process

275 The first three recommendations emerged from the first, second and third deductions. These  
276 recommendations are considered the pillars to achieve effective consideration of LCA in bridge  
277 design. The final recommendation is based on the fourth deduction, which suggests that LCA  
278 awareness should be increased amongst bridge designers, which is currently low, as evident  
279 from the interview outcome.

## 280 **6. Conclusions**

281 This investigation has revealed that the environmental aspect of sustainability is minimally  
282 considered in bridge design, and sustainability itself is only appraised in five major areas, which  
283 do not effectively account for detailed environmental issues. These five areas are the need for  
284 the bridge, access to future maintenance, use of quality materials, consideration for long life  
285 with little amendment, and cost saving options. Further, protection of flora, fauna, watercourses,  
286 and surrounding environment are the main environmental checks undertaken for bridge  
287 maintenance works. In fact, only nine drivers determine the choice of a maintenance solution,  
288 which are as follows: finance, speed of completion, funding choices, functionality,  
289 maintainability, minimal disruption to traffic, construction technique, and constructability. This  
290 excludes environmental emissions such as CO<sub>2</sub>, NO<sub>2</sub> and other GHG emissions associated with  
291 the actual maintenance functions.

292 Similarly, the interviews revealed that sustainability is still a “tick box exercise” for the bridge  
293 industry, and not much environmental detail is considered. On this note, emergent  
294 recommendations largely concern bridge designers and bridge owners. However, the  
295 government will play a major role in their implementation. For instance, the recommendation for  
296 CO<sub>2</sub>, NO<sub>2</sub> and other GHG emissions being considered as a design criterion will be taken  
297 seriously (by designers and bridge owners) only if a bill is passed on that matter; otherwise, it  
298 will be business as usual. The same goes for the recommendation, “LCA awareness should be  
299 heightened amongst bridge designers to increase potential usage”. This paper sets the stage for  
300 further studies in the areas of LCA implementation (i.e. funding, awareness, training etc)

301

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305

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