Life-cycle assessment 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_2 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_2 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_2, NO_2 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

Introduction

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

2. A Review of LCA application to bridges

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

Santero, et al. (2011) have worked on LCA of asphalt pavement. Table 1 presents an overview of review papers published within the last 8 years on buildings, roads and bridges, and of the papers reviewed, only one was specific to bridges. Bridge LCA has mainly been used for comparison purposes (i.e. comparing different bridge forms, materials, components, and design elements). However, only a small body of literature has compared bridge maintenance methods (Steele et al., 2003; Pang et al., 2015, Balogun et al., 2018), though none has considered experts' opinion on incorporating the tool itself into bridge design, as presented in this study. Table 2 presents case studies comparing bridge forms, elements, components, materials and design using LCA methodologies. It was evident that only the superstructure (deck component) of the bridge was accounted for, mostly, and only a handful considered sub-structural components. Impact assessments principally considered are CO_2 emissions and energy with depletion of abiotic resources, acidification, eutrophication, climate change, ozone layer depletion, and photo-oxidant creation, and possibly an attempt to contribute to the on-going global debate. Generally, it can be inferred that results were largely determined by the input parameters of Life Cycle Inventories (LCI), system boundaries and impact assessment methodologies adopted. Therefore, even the same bridge under a different scenario can yield a different result, more so as there is a high level of uncertainty about the data collected. Although Zhang, Wu and Wang (2016) tried to address uncertainty issues in LCA of bridges through sensitivity analysis, it does not change the fact that data availability is the root cause for most uncertainty problems in bridge LCA studies and perhaps justifies the need for experts to validate the practical relevance of the outcome. Similarly, only issues of uncertainties, functional units, data availability, system boundaries, methodology and impact assessment categories have been addressed (Crawford 2011; Du and Karoumi 2014; Panesar, et al., 2017) and limited attention paid towards how interpreted results will support decision making, considering that many of these results are subject to the shortcomings. Du et al. (2014), for example, struggled to reach a convincing conclusion and asserted that only a comprehensive LCA that considers all impact categories could allow a detailed conclusion to be reached. More so, the choice of what to include in the analysis depends solely on the investigator (Crawford, 2011; Du et al., 2014; Pang et al., 2015). According to Cowell (1998), the usefulness of LCA results is measured through four criteria: accuracy, relevance, comprehensibility, meaningfulness, and acceptability as a legitimate form of analysis. While these criteria are vaguely considered, stakeholder engagement can help the researcher understand this matter a lot more (Shiels, 2005; Selmes, 2005; Sala, et al, 2013). None of the case studies presented the usefulness of the result through a structured approach. Exploring the usefulness of bridge LCA results will potentially aid practical implementation and wider applicability of LCA, considering that its application is still limited in the bridge industry. The limited application can be traced to a lack of knowledge and awareness (Tan, et al., 1999; Crawford, 2011), and possibly doubts regarding the integrity of the results. However, to fully understand environmental sustainability and the integration of LCA tool in the bridge design process, the following questions need to be addressed:

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

3. Methodology

Given the need to identify expert opinion on the usefulness of LCA in bridge design, in-depth semi-structured interviews were conducted with 21 industry experts identified through a snow ball sampling strategy. Interviewees included nine bridge designers, eight bridge engineers, one design manager, one renewal engineer and one asset engineer. Interviewees spanned the range of major bridge owners, clients, contractors, and consultants in the UK bridge industry. The background of participants in the study is presented in Table 3. Selection criteria for interviewees are as follows: minimum 15 years of work experience and a university degree. Interviewees were allowed to develop their own story and all interviews were recorded and transcribed as a Microsoft Word document. The transcribed document was read severally, edited, and organised into a suitable format before being fed into NVivo 11 (a qualitative data analysis software package) for analysis. Coding in NVivo package is used to store important extracts from the transcript and there two main types, selective coding and complete coding. Selective coding is a deliberate selection of instances relating to the phenomena of interest and requires pre-existing theoretical and analytical knowledge of the phenomena of interest (Braun and Clarke, 2013). Complete coding, on the other hand, does not look for particular instances within the dataset, but aims to identify anything and everything of interest or relevance to the research question (Saunders et al, 2012). In line with this, the paper opted for complete coding and captured any relevant information useful for answering the research question. As such, phrases and words identified to provide answers to research questions one, two and three were coded accordingly. Developing themes involves a thorough review of similar codes with the hope of identifying similarities and overlap between them (Braun and Clarke, 2013). Identifying themes allows concepts and issues with similar focus to be gathered under a central organising concept. Therefore, a theme can capture vital information about the data in relation to the research question (Bazeley, 2013). On this account, the codes identified were sorted into potential themes. According to Braun and Clarke, (2013) themes appear on three main levels. These are as follows:

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

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

4. Results and Discussion

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

4.1 Which sustainability criteria are factored into new bridge design?

Interviews with experts revealed five areas (depicted in Figure 1) where sustainability is appraised in bridge design. Unfortunately, sustainability issues go beyond these areas, as elements of the triple bottom-line approach (environmental, economic, and social) need to be fully incorporated. For instance, cost, programme, aesthetics, constructability, health and safety, maintainability, environmental issues and so on need to be considered (Collings, 2006). At this time, predominant issues identified in the interviews as revealed in Figure 1, cover only economic and social aspects in some way, but not environment. Zhang (2010) equally agrees with these issues, yet, there is need to consider more environmental matters, as other sustainability elements depend on it to thrive (Selmes, 2005; Ainger and Fenner, 2014). In fact, Interviewee (N) informs that sustainability in bridge design is considered from the aspect of access to future maintenance and interviewee (E), states, '… *So you design a bridge in such a way that you can get to the bearing to take out the existing bearing and replace with new one, whether you think they are going to need replacement or not, you always make provisions, so they can be done.'* Moreover, attention is increasingly being drawn to environmental matters stemming from the risk and uncertainty of resource depletion, CO_2 emissions and other Green House Gas (GHG) matters (UN, 2015). Interviewee (D) made an interesting point that environmental sustainability in bridges can be a casualty, if cost is the motivating factor. Interviewee (D) expressed, *'… You could have several structural engineers designing bridge works to minimise carbon foot print; but then the people who undertake the work who source the material could undermine it by bringing materials from overseas with all the transportation cost because it works out cheap for them'*

Moreover, interviewees revealed that protection of flora, fauna, surrounding environment and watercourses are the only sustainability considerations accorded to bridge maintenance works, although these checks are a statutory EIA requirement, and align with Yeang's (2010) recommendation for achieving a green built environment. According to Interviewee D, '… *It has always been about avoiding any harmful material from getting into the watercourses, avoiding salt being kicked up into watercourse, avoid disturbing the flora and fauna in or around the watercourse and that's always been the main environmental drive.'* Environmental emissions (such as CO_2, NO_2, SO_2 and so on) from the actual maintenance work are still being neglected. The bridge industry, however, needs to shift from the traditional cost driven approach and embrace a more environmentally- friendly approach, especially at the design stage, where every choice will affect the long-term sustainability performance of the bridge.

4.2 What are the drivers of structural or maintenance solutions?

Interviewees revealed that clients are the major determinants of structural choices, and their choices are based on construction cost and long-term maintenance cost. According to Interviewee I, *'sustainability is one of those tick box exercises to say yes, we are environmentally friendly all those kind of stuff, but it depends on how you define sustainability, you want a structure which has long life which is 120 years with little amendments.*' It follows that designers need to suggest and justify sustainable options to clients. Suggestions can be accepted or rejected depending on the depth of justification (Wessels, 2014). Assessments such as CEEQUAL are developed to facilitate such justification and reward projects that demonstrate detailed sustainability considerations (CEEQUAL, 2017). Apart from the areas revealed in Figure 1, nine other drivers are revealed in Figure 2 (from the interview), which determine the choice of bridge maintenance actions. These drivers take precedence before any environmental matter is considered. Whiles Interviewee L stated, '… *When we have a programme of work to do, how we go about that and the choice we make is influenced by – does that affect our funding or not, if it doesn't affect our funding, we do it as we've always done it. If it starts to affect or reduce our funding or gives us the need to increase our funding then we change the way we work, it is as simple as that really…'* Interviewee N agrees: *'… the drive is to apply certified quality material which will provide functionality and durability for the design life which itself it's a prerequisite so you don't have to build the thing again in 20 years' time...'* However, interviewee L feels, '… *Sustainability is a big issue at the moment and is a key factor when designing new structures in terms of environmental impact assessment. If you can prove* *that your option is low or less impactful, then it would certainly be favourable by funding authorities. May be cost a little bit more but being a greener structure, that would help because cost these days doesn't mean we shouldn't be skimping out and creating problems latter on'* . As such, LCA may soon be an essential part of the decision-making process, as funding bodies are beginning to reward projects that demonstrate substantial environmental life cycle performance in terms of emissions. As environmental concerns are increasingly becoming a global concern and need to be considered in structural and maintenance solutions, designers may need to advise clients on issues of resource depletion, energy use, and CO_2 emissions at the early design stage or maintenance phase in line with their choice, with reasonable justifications. Otherwise, bridge designers will struggle to consider detailed environmental issues in their design. Materials and methodologies that lead towards minimal maintenance are also considered in design and maintenance choices. The use of alternative methods and materials to address environmental issues in bridges aligns with Zhang (2010). However, client choices and the designers' justifications play a major role in making these decisions.

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

Interviews revealed that LCA awareness is limited amongst bridge engineers, let alone its usage. This was obvious from the interview conversations, as little interest was shown in the LCA methodology. Interviewee D reveals, '… *There is a life cycle assessment done but not formally with decision making about what route you are taking. I haven't come across a life cycle assessment where it is taken into account how much CO_2 is gonna be used for construction or during a planned maintenance. If that makes sense, so it doesn't really come into it'*. Moreover, interviewee (L) explains that the environmental effect of bridge maintenance can be negligible, in the sense that only a small portion of the bridge needs to be replaced with like-for-like parts, which may not necessarily require environmental assessment. Interviewee (E) highlights – *' In terms of maintenance, we don't think a lot about environmental effect, but we do try and think and make things that can be maintained*.' On the other hand, interviewee (K) argues that major clients largely consider life cycle issues during decision-making (e.g., whole life cost; life cycle cost; etc.). Interviewee (K) reveals that, '… *If we decide to replace it, part of our renewals team, we pass the bridge onto effectively program manage all of the replacement works, but part of*

their scope and tender submission or things like that would have life cycle cost within it, life cycle maintenance and all that kind of stuff within it and helps us decide what the best option is.'
Experts claimed that LCA midpoint indicators were too complex to be incorporated into the design process. However, there could be room to incorporate the endpoint indicators. LCA was considered for only new constructions, if at all, but never for existing bridge maintenance work. According to Pang et al. (2015), LCA for bridge maintenance action is limited. However, failure to consider LCA for bridge maintenance action could impinge upon UK's effort to reduce CO_2 emissions by 2050. This stems from the fact that maintenance actions improve the serviceability and longevity of bridges, and require substantial material consumption (over a life span), with the relative impact on the environment. More so, maintenance output accounts for the highest value amongst the UK component parts (year in year out) (ONS, 2013, 2014, 2015, 2018), and should be taken seriously. The reality, however, is that design-maintenance process is already a complex one (Riches, 2003), and incorporation of LCA methodology could compound the complexity, even though the environmental indicators offered through LCA are becoming important sustainability matters (UN, 2015). The interviews revealed that there may be scope to include the damage indicators (that is resource depletion, ecosystem, and human health) of LCA in bridge design, even as the desire to factor environmental considerations into bridge design is growing (Du et al., 2014). LCA however is mainly suited to a definite system, which requires components, process, and material data to be precise (Millet et al., 2007). Unfortunately, precise data for bridges are scarce, and estimates and assumptions will need to be made (Du and Karoumi, 2014; Hammervold et al., 2013).

5. Development of recommendations

Deductions from the above discussions will underpin the development of recommendations for integrating LCA into bridge design and maintenance. The first deduction emerging from the findings attributed to question one, which informs that bridge designers can suggest the considerations of more environmental indicators such as resource depletion, energy, CO_2 and so on to clients, as the least they could do to influence sustainable decisions. However, this will require appropriate justification in the design brief. LCA becomes a useful tool in this regard. A second deduction also emerged from findings attributed to question one. This revealed that sustainability is still a tick box exercise in the bridge industry and that vital environmental concerns such as CO_2, NO_2, and other GHG emissions are neglected in bridge maintenance work. Rather, protection of flora, fauna, environment and watercourses are more significant concerns. However, environmental issues of CO_2, NO_2, and other GHG emissions are becoming more pressing environmental concerns and should be factored into bridge maintenance operations, in adherence to UK's Climate Change Act, associated carbon emissions commitment and legal obligations placed on the infrastructural sector. LCA could be applied to achieve this purpose based on previous studies. Further, CO_2, NO_2, and other GHG emissions associated with maintenance work can be revealed and the result can guide sustainable maintenance and design choices.

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

A set of recommendations have emerged from the deductions presented. Recommendations will pave the way for general integration of LCA into bridge design. These recommendations can help the bridge industry contribute towards the environmental sustainability development goal relating to the overall built environment. Providing recommendations towards the improvement of environmental sustainability practices in the built environment sector is not unusual (CIRIA, 2006). However, recommendations derived from expert input through semi-structured interviews are not yet available to the UK bridge industry. Although Zhang (2010) presented some recommendations to help bridge designers improve practice and contribute towards CO_2 reduction, they did not consider expert input. The recommendations presented in this study are as follows:

1. Detailed environmental matters such as CO2, NO2 and GHG emissions should be considered as design criteria;
2. Designers should be encouraged to highlight emerging environmental matters in the design brief; (3)
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

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

6. Conclusions

This investigation has revealed that the environmental aspect of sustainability is minimally considered in bridge design, and sustainability itself is only appraised in five major areas, which do not effectively account for detailed environmental issues. These five areas are the need for the bridge, access to future maintenance, use of quality materials, consideration for long life with little amendment, and cost saving options. Further, protection of flora, fauna, watercourses, and surrounding environment are the main environmental checks undertaken for bridge maintenance works. In fact, only nine drivers determine the choice of a maintenance solution, which are as follows: finance, speed of completion, funding choices, functionality, maintainability, minimal disruption to traffic, construction technique, and constructability. This excludes environmental emissions such as CO_2, NO_2 and other GHG emissions associated with the actual maintenance functions.

Similarly, the interviews revealed that sustainability is still a “tick box exercise” for the bridge industry, and not much environmental detail is considered. On this note, emergent recommendations largely concern bridge designers and bridge owners. However, the government will play a major role in their implementation. For instance, the recommendation for CO_2, NO_2 and other GHG emissions being considered as a design criterion will be taken seriously (by designers and bridge owners) only if a bill is passed on that matter; otherwise, it will be business as usual. The same goes for the recommendation, “LCA awareness should be heightened amongst bridge designers to increase potential usage”. This paper sets the stage for further studies in the areas of LCA implementation (i.e. funding, awareness, training etc)

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