 Copyright 2017 by the Associated Schools of Construction

Carbon Dioxide Equivalency as a Sustainability Criterion for Bridge Design Alternatives

Vaishak Gopi, M.S., Bolivar Senior, Ph.D., John van de Lindt, Ph.D., Kelly Strong, Ph.D., and Rodolfo Valdes Vasquez, Ph.D.,
Colorado State University
Fort Collins, Colorado

The carbon dioxide equivalent quantity (CO2e) embodied in the superstructure of a sample of 21 steel and 15 prestressed concrete bridges was used as the criterion to analyze their sustainability level. Greenhouse gases other than CO2 were incorporated as multiples of their effect compared to CO2, resulting in a total CO2 equivalent (CO2e) metric. The analysis required quantity takeoffs, which were based on publicly available information for each bridge. Secondary factors such as construction time and the average distance of materials from the jobsite were also included in the analysis. An existing environmental analysis software package was used to perform the computations. Results were normalized by deck area, by the number of traffic lanes and by width, and ranked by CO2e concentration from superior to unacceptable performance. The findings show significantly better rankings for prestressed concrete deck structures compared to their steel counterparts. Future studies will include larger sample sizes drawn from across the U.S. to validate the current results.

Key Words: CO2, Bridge, Sustainability, Heavy highway construction, Quantitative research.

Introduction

The degradation of the planet's environment is a subject of concern, especially by the growing evidence of global warming. A primary factor identified as a reason for global warming is the greenhouse effect resulting from the increasing volume of gases harmful to the environment generated by natural causes and as byproducts of human activity, mainly after the Industrial Revolution. A small number of greenhouse gases (GHG) account for most of the effect, namely water vapor, carbon dioxide (CO2), methane, nitrous oxide, and ozone. CO2 is of special concern, since its concentration in the atmosphere has increased significantly over the past century, compared to the rather steady level of the pre-industrial era (about 280 parts per million in volume, or ppmv). The 2012 concentration of CO2 (396 ppmv) was about 40% higher than in the mid-1800s, with an average growth of 2 ppmv/year in the last ten years. Significant increases have also occurred in levels of methane (CH4) and nitrous oxide (N2O) (International Energy Agency, 2015).

Construction has been found to be a major source of GHG, and its environmental impact has been studied for decades (e.g, Korkmaz, 2012; Orabi, Zhu and Ozcan-Deniz, 2012). In the USA, buildings account for 38% of all of the CO2 emissions and 73% of electricity consumption (US Green Building Council, 2016, US Department of Energy, 2011).

The green construction movement has risen in response to the perceived need for more environmentally-friendly construction projects. The need to incorporate green factors into project design and construction has been evidenced by the increasing recognition of green rating systems such as the Leadership in

 Copyright 2017 by the Associated Schools of Construction

Energy and Environmental Design, LEED (U.S. Green Building Council, 2016) and the Building Research Establishment Environmental Assessment Methodology, BREEAM (Baldwin et al., 1998). These rating systems generally emphasize building design and construction, with only a few centering on heavy construction such as roads and bridges (Spencer et al., 2012, Shivakumar et al., 2014). The reduced number of infrastructure-oriented rating systems has led to limited guidance for heavy construction designers about the impact of their design decisions on the sustainability of their projects.

One of the few alternatives providing a framework for infrastructure construction sustainability ranking is the Envision rating system, developed with the collaboration of the Institute for Sustainable Infrastructure and ASCE (Clevenger, Ozbek and Simpson, 2013). It has five main categories: quality of life; leadership; resource allocation; natural world; and climate and risk. Despite Envision's suitability for the detailed ranking of infrastructure projects, currently there are no certified projects in the area of heavy bridge construction. Most of its certified project to date relate to water infrastructure (Huang, 2014, Qualls et al., 2015). The details of Envision and other systems emphasizing infrastructure projects are discussed by Clevenger et al. (2013).

Most heavy construction projects consist of relatively few, significant elements in tight mutual dependency compared to building projects (a bridge's span segments, for example, influences its type of structure, which in turn influences its foundations, and depending on geotechnical factors, the loads supported by the foundation influence the required bridge span segments). The mutual dependency of bridge components has allowed the development of parametric cost estimating systems (Chou, Wang, Chong, and O'Connor, 2005) and suggests that the embodied energy of a bridge can be analyzed parametrically, depending on its type of structure (e.g., steel, prestressed concrete) and its size.

While LEED and similar sustainability rating systems need the consideration of dozens of factors leading to prescriptive requirements (USGBC, 2016), there is potential for the assessment of the sustainability of bridge construction (particularly the amount of equivalent CO2 embodied by the bridge structure) using a simpler approach.

Embodied CO2 has been addressed by previous research. Haynes (2010) presents a case study of residential construction, basing his estimate on an extensive list encompassing the CO2 embodied by each construction element. Hammond and Jones (2008) also estimate the CO2 for several buildings by performing a comprehensive analysis of each intervening construction part. They observe that "comparative estimates of embodied carbon values are quite rare within the construction literature."

Research Approach

This study performed a systematic assessment of the CO2e embodied by the superstructures of a sample of trunkline bridges in the state of Colorado, U.S.A. The research addresses the challenges of assessing CO2 equivalent emissions (CO2e) and creating a sustainability ranking scale based on the embodied CO2e of each bridge. An overview of the research method followed by this study is shown in Figure 1.

Copyright 2017 by the Associated Schools of Construction

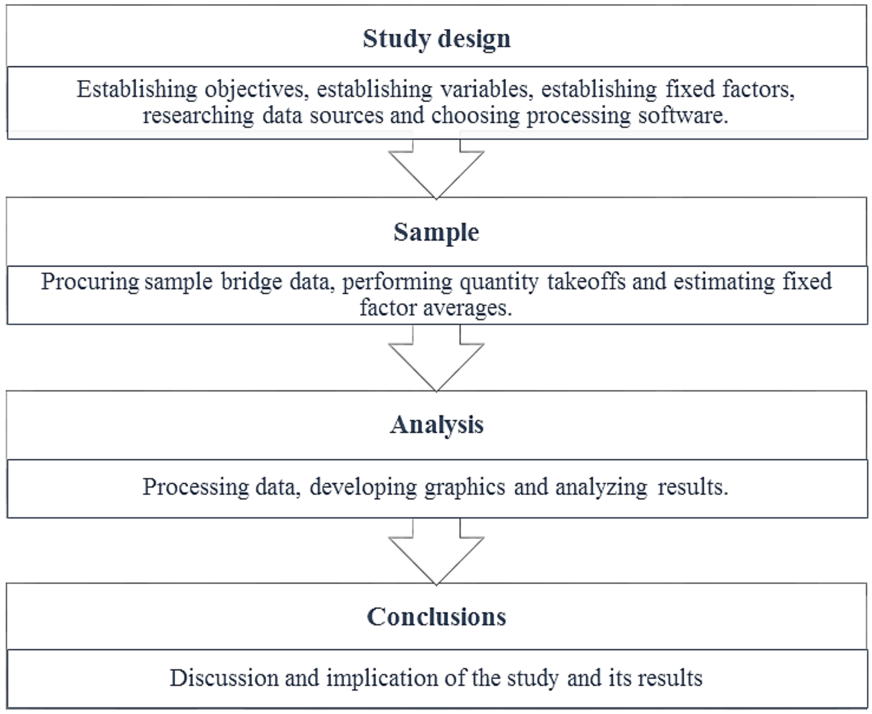

Figure 1: Research method overview

For this study, 36 trunkline bridges from Colorado Department of Transportation were randomly selected. All of these bridges were constructed after 1990 and had a span length of at least 200 feet. Moreover, the bridges chosen had main structural elements of either prestressed concrete or steel, two design alternatives that are commonly used and allow for a richer contrasting analysis for embodied CO2e. Although some GHGs are considerably more destructive that CO2, this latter gas pervasiveness in the environment has led to estimating the environmental load of all GHGs in CO2 equivalent amounts, or CO2e. Table 1 shows the global warming potential (GWP) of these GHG as multipliers of their CO2e, which were used in this study to express all embodied GHG using CO2e as a single variable.

Table 1

Global warming potential for key GHS (EA Tool™, 2013).

GHG	**GWP Factor (Equivalent CO2)**
Carbon dioxide	1
Dinitrogen monoxide	310
Methane	21
Methane, HCC-30	9

 Copyright 2017 by the Associated Schools of Construction

The study analyzes the CO2e embodied in the superstructure of the bridges in the sample. The analysis was limited to the bridge superstructure due to the significant influence of geographical and geotechnical factors on other structural elements, especially the substructure and foundations systems.
Structural drawings for each bridge were obtained from the Colorado Department of Transportation. The amounts of concrete and steel used in the construction of the superstructure were quantified for each bridge from this information, and were the main drivers for the amount of embodied CO2e. Other factors of less significance in terms of their effect on the total CO2e used for the analysis are shown in Table 2. Average figures were used for these factors, based on the analysis of part of the sample and the authors' personal experience.

Table 2

Study assumptions and factor definition

#	Assumption	Factor definition
1	CO2 content is representative of bridge sustainability	CO2e
2	Area of the bridge	Deck Length (ft) x Deck width (ft)
3	Average days to construct	90 days
4	Service life	75 years
5	Main material	Steel or prestressed concrete
6	Distance travelled by concrete before pouring via road	100 miles
7	Distance travelled by steel before erection via road	560 miles (Plymouths, UT to location)
8	Average strength of concrete	5-7 ksi
9	Steel fabrication level	0.020Kg/ton

The Environmental Analysis (EA) Software Tool (EA Tool™) created by Skidmore, Owings & Merrill LLP (SOM) was used to quantify the embodied CO2e of each bridge. The EA software package measures the equivalent CO2e for all the GHGs, including CO2, contributing towards a 100-year global warming potential. The software comprises data from various organizations including the National Renewable Energy Laboratory (NREL), University of Bath, Inventory of Carbon and Energy, Portland Cement Association (PCA), California Energy Commission, Carnegie Mellon University and the South Coast Air Management District. The software "with minimal information such as geographic location, number of floors and floor area designers can quantify equivalent carbon emissions embodied in a structure at early conceptual stages of design." (EA Tool, 2013). The details of the algorithm used by the software are proprietary.
Table 3 provides an example of the CO2e required to produce one kilogram of steel, as provided by the EA software for the assumptions of this study. The inputs of the EA software include the contribution of materials, construction, and demolition. Fabrication for other steel components such as nuts, bolts and rebar were not considered, since they are largely manufactured without the need for any further fabrication. Emission by typical construction equipment for the 90-day construction period was also included in the estimates.

Table 3

Equivalent CO2 content for 1 kg production of steel components

For 1.0 kg of steel	Emission (Kg)	Factor	Emission (Co2e Kg)
Embodied carbon dioxide	2.27118	1	2.27118
Other GHG's:			
Dinitrogen monoxide	3E-06	310	0.00081
Methane	0.00113	21	0.02371
Methane, HCC-30	0	9	0
Nitrogen oxides	0.00282	0	0
Non-methane VOCs	0.00107	0	0
Carbon monoxide	0.02491	0	0
Total Equivalent Embodied Carbon Dioxide:			2.2957

The CO2e consumption for each bridge was tabulated along with the CO2e data from other bridges. The results were plotted in an empirical distribution function and then normalized as CO2e embodied per deck square foot (tons/sf). They also were checked for two additional criteria, namely deck width and number of traffic lanes. Performance in terms of embodied CO2e was subjectively categorized by the researchers into five brackets ranging from superior to poor using the shape of the empirical distribution function for embodied CO2e normalized for per square foot of deck area. The cumulative Weibull function (a flexible distribution used to fit empirical data such as failure rates) was used as a secondary tool to test the statistical coherence of results.

Results and Discussion

Figure 2 shows an empirical distribution plot of the CO2e embodied by the 36 trunkline bridges considered in this study. The embodied CO2e ranged from 1,400 tons to 18,000 tons. This wide range was expectable as partly due to differences in size and was compressed when results were normalized as CO2e per square foot of deck area, shown in Figure 3. Moreover, results were normalized by deck width and number of lanes, as shown in Figure 4.

The empirical distribution plots are shown in Figures 2 to 4 have similar shapes, with a significant percentage of their ordered sample progressing from a small CO2e per standardized unit to a large spread of CO2e concentration at the higher amounts of embodied CO2e per standardized unit. This consistent shape led to the ranking categories shown in Table 4, from superior performance for bridges with embodied CO2e per square foot of deck in the lowest 20% of the sample to unacceptable for bridges in the highest 10%. The thresholds for each category were subjectively chosen by the authors based on the plot shape. The plot's shallow slope for the two lower categories of Unacceptable and Poor led to brackets of 10% for each one. Conversely, the plot shows a steep slope for the intermediate categories of Acceptable and Excellent, and a bracket of 30% was chosen for each one. The Superior category was assigned to the top 20% of the sample, that is, the bridges with the least amount of embodied CO2e per square feet of deck.

 Copyright 2017 by the Associated Schools of Construction

The Weibull function showed a moderate goodness of fit, with an $R^2 = 0.78$ (The fitted function was defined by an intercept = 4.80, a shape parameter = 2.62 and a scale parameter = 0.16). The relatively small sample size does not allow a definite judgement about the possibility of using a mathematical formula relating deck surface to embodied CO2e.

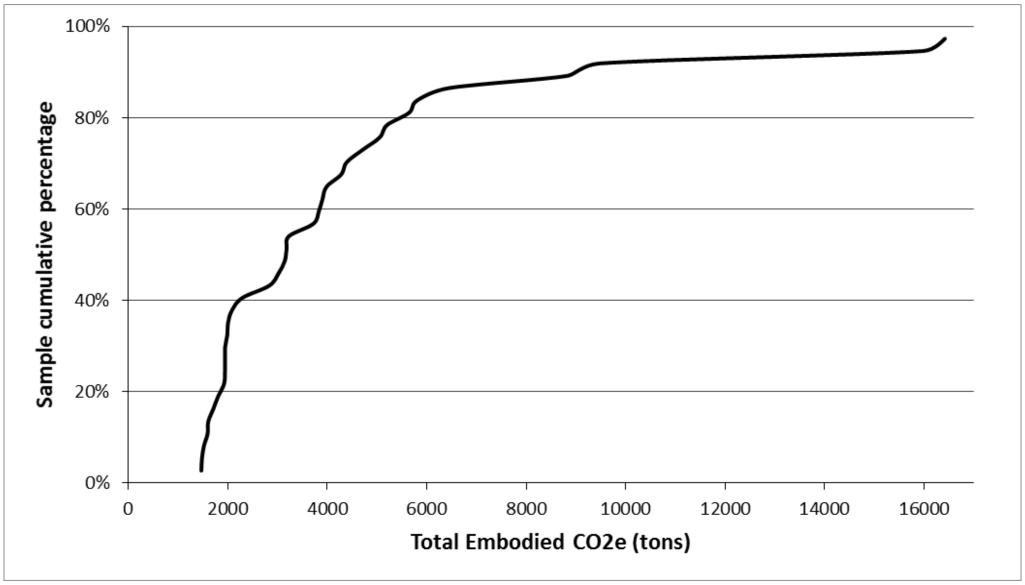

Figure 2: Empirical distribution plot of total embodied CO2e by the sample bridges

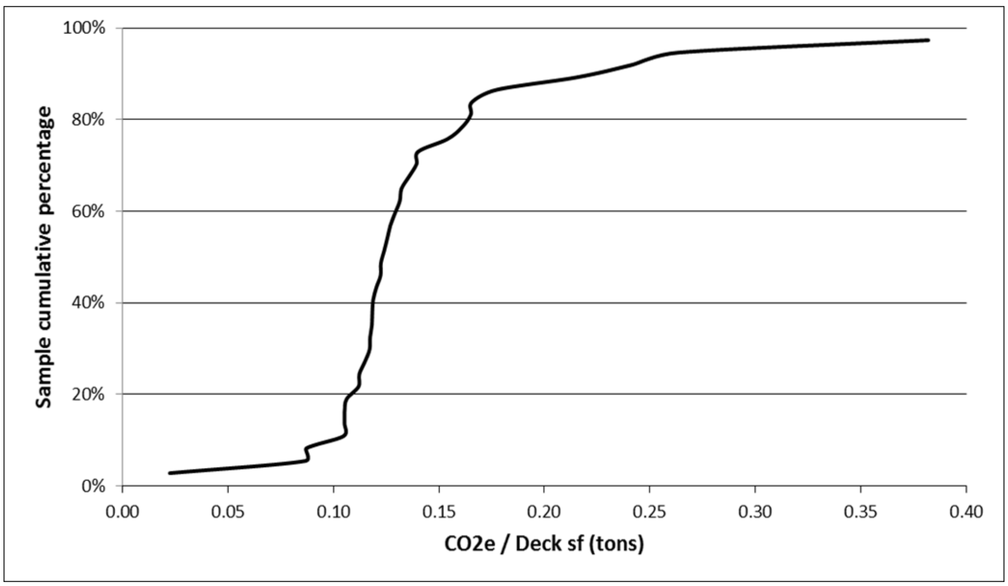

Figure 3: Empirical distribution plot of normalized embodied CO2e per square foot of deck area

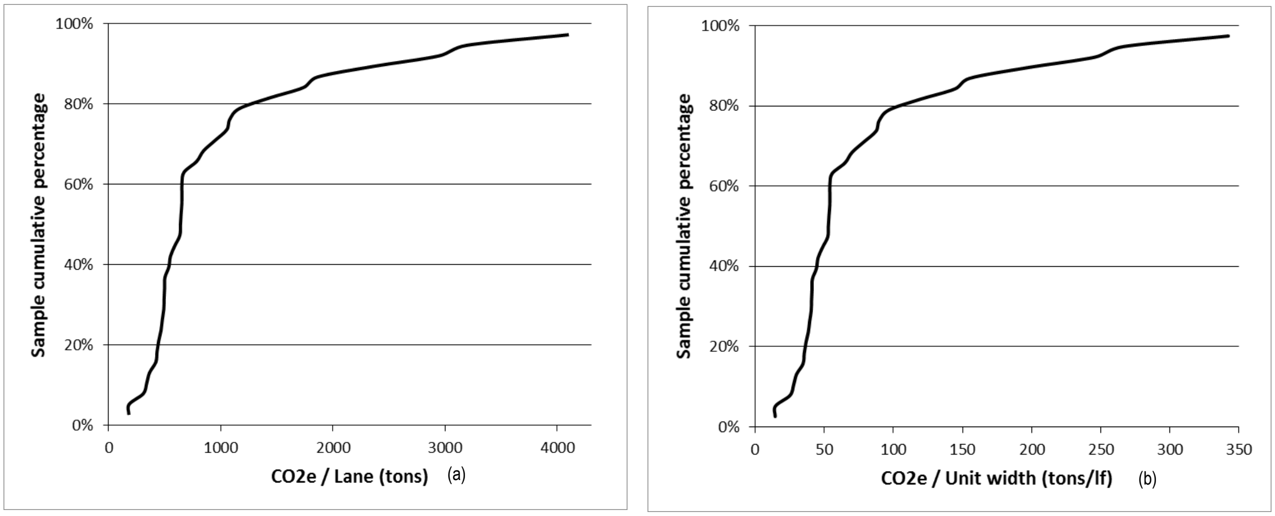

Figure 4: Empirical distribution plot of normalized embodied CO2e per unit width and number of lanes

Table 4

Ranking categories, embodied CO2e per square foot of deck area

Position on CDF	Corresponding ranking
$0 \geq y \geq 0.2$	Superior
$0.2 > y \geq 0.5$	Excellent
$0.5 > y \geq 0.8$	Acceptable
$0.8 > y \geq 0.9$	Poor
$0.9 > y \geq 1.0$	Unacceptable

The two types of bridge superstructures considered in the sample, namely prestressed concrete and steel, were ranked according to the brackets defined in Table 4. The results of this grouping are shown in Table 5. For the sample, prestressed concrete deck structures embody less CO2e than steel deck structures, as reflected in a proportion of 2:1 favoring prestressed deck concrete in the categories of Acceptable to Superior, and 1:6 in the Acceptable, Poor and Unacceptable categories, also favoring concrete.

 Copyright 2017 by the Associated Schools of Construction

Table 5

Sample ranking by type of deck structure

Deck Structure	**Acceptable to Superior**	**Acceptable to Unacceptable**	**Total in sample**
Concrete	12 (66.7%)	3 (14.3%)	15
Steel	6 (33.3%)	15 (85.7%)	21

Results indicate significantly better rankings for prestressed concrete deck structures compared to their steel counterparts. However, this study included a relatively small number of bridges and assumed average values for some performance variables, as shown in Table 2. Results should be interpreted as exploratory, which must be probed in more detail by a larger study.

Conclusion

The need for sustainable construction becomes increasingly evident. In the case of trunkline bridges, there can be competing designs of very similar cost and effectiveness, but whose environmental effects can be different and yet not considered in the choice of one design over another. It is proposed that sustainability criteria should play a significant role in such design decisions.

This study shows a systematic approach for the input and processing of trunkline bridge decks. A designer can follow this process to find the embodied CO2e in a particular design, and use a curve similar to the one shown in Figure 3 to estimate the performance of the deck from a sustainability perspective.

The use of CO2e as the criterion for the design's sustainability is a simplification of the factors that can influence the sustainability of a structure. However, the nature of heavy construction has shown that important estimates such as the bridge's cost can be determined by using a single or few parameters.

The ranking scale from Superior performance to Unacceptable performance, although subjectively determined by the researchers, was the result of a careful consideration of empirical distribution plots for the sample bridges using several grouping criteria. The scale brackets serve as a narrative of the graphical and numerical results of the study. It is considered that the method and findings of this research would not be altered in any significant way by the adoption of different thresholds for each bracket. A larger study should encompass a larger bridge sample across a wider geographic distribution, and should explore the addition of additional quantifiable factors. Moreover, establishing a mathematical relationship between a bridge's CO2e and its structure surface would open wider opportunities for a simple, parametric estimating of its embodied CO2e. A larger sample size is also required to explore this promising possibility, which could lead to a reliable and simple approach to gauge a bridge's sustainability.

 Copyright 2017 by the Associated Schools of Construction

Acknowledgement

The authors thank the U.S. Department of Transportation and Mountains and Plains Consortium for its financial support to this study.

References

Baldwin, R., Yates, A., Howard, N., & Rao, S. (1998). *BREEAM 98 for offices: an environmental assessment method for office buildings*. Garston: Building Research Establishment Ltd, 5.

Chou, J. S., Wang, L., Chong, W. K., & O'Connor, J. T. (2005, April). Preliminary cost estimates using probabilistic simulation for highway bridge replacement projects. In *American Society of Civil Engineers, Construction Research Congress* (pp. 939-948).

Clevenger, C. M., Ozbek, M. E., & Simpson, S. (2013, April). Review of sustainability rating systems used for infrastructure projects. In 49th ASC Annual International Conference Proceedings (pp. 10-13).

Environmental Analysis Tool (EA Tool), version 1.0.0 [Computer Software]. (2013). Skidmore, Owings & Merill (SOM) LLP. Retrieved from https://somhpd.com/eatool/

Environmental Protection Agency (EPA). 2013. *Sources of Greenhouse Gas Emissions*. Retrieved from http://www.epa.gov/climatechange/ghgemissions/sources.html.

Hammond, G. P. and Jones, C. I., 2008. Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy*, 161 (2), pp. 87-98.

Haynes, R. (2010, revised 2013). *Embodied energy calculations within life cycle analysis of residential buildings*. Retrieved from http://etoolglobal.com/wp-content/uploads/2012/10/Embodied-Energy-Paper-Richard-Haynes.pdf.

Huang, C. (2014, November). Sustainable Pedestrian Bridge Design: A Discussion of the Envision Rating System. In International Conference on Sustainable Infrastructure 2014.

International Energy Agency (2015). *CO2 Emissions from Fuel Combustion Highlights (2015 Ed.)*. Retrieved from https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2015. pdf.

Korkmaz, K. A., Syal, M., Harichandran, R. S., & Korkmaz, S. (2012). Implementation of Sustainability in Bridge Design, Construction and Maintenance (No. RC-1586).

Orabi, W., Zhu, Y., & Ozcan-Deniz, G. (2012). Minimizing greenhouse gas emissions from construction activities and processes. In *Construction Research Congress 2012: Construction Challenges in a Flat World*, 1859-1868.

Qualls, S. A., Bowles, E. C., & Bradley, N. (2015). From Nashville to New York City Practical Applications of the Envision Rating System. Proceedings of the Water Environment Federation, 2015(8), 4413-4431.

Shivakumar, S., Pedersen, T., Wilkins, S., and Schuster, S. (2014) Envision: A Measure of Infrastructure Sustainability. *Pipelines 2014*, 2249-2256.

Spencer, P. C., Hendy, C. R., & Petty, R. (2012, June). Quantification of sustainability principles in bridge projects. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering*, 165 (2), 81-89.

U.S. Department of Energy (2011). *Buildings Energy Data Book*. Buildings Technologies Program Energy Efficiency and Renewable Energy. Retrieved from http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2011_BEDB.pdf. [Reference list will be updated]
U.S. Green Building Council (2016). LEED v.4 for New Building Design and Construction. http://www.usgbc.org/leed, 2016.