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Life Cycle Assessment for a Concrete Bridge using Open LCA Software

Prasanna SVSNDL[1*], *Sanjana* Alugubelli[2], *Yashwanth* Pamu[3]

[1] Department of Civil Engineering, University College of Engineering, Osmania University, Hyderabad, India
[2] Department of Civil and Environmental Engineering, University of California, Davis, 95616, CA, USA
[3]Department of Civil Engineering, CVR College of Engineering, Hyderabad, India

Abstract. This study evaluates the environmental impacts associated with the construction phase of a concrete bridge in Hyderabad using Open LCA software and the Ecoinvent v3.9.1 database. The analysis covers major structural components like foundation, piers, abutments, deck slab, crash barrier, wearing coat, return wall, and approach slab and key construction materials such as cement, sand, aggregates, and reinforced steel. Life Cycle Impact Assessment was conducted using ReCiPe Midpoint v1.03 (H), Eco-Indicator 99, and Ecological Footprint methods to quantify impacts across categories such as global warming potential, acidification, and ozone depletion. Results indicate that cement is the most environmentally burdensome material, contributing approximately 10,105,721 m²a of carbon footprint, due to its energy-intensive manufacturing process. Aggregates recorded the lowest impact (0.0015 kg CFC eq) due to its minimal processing requirements. Among structure components, the foundation exhibited the highest environmental load, with carbon footprint of 4,846,171 m²a, primarily from its large concrete and steel volumes, while the approach slab had the lowest impact. The findings highlight the need for sustainable material selection and design strategies during construction to reduce environmental footprints. Recommendations include substituting high impact materials with supplementary cementitious materials and exploring recycled aggregates for future projects.

Keywords: Environmental Impacts, Open LCA, Sustainability, ReCiPe Midpoint, Eco-Indicator

1 Introduction

Life cycle assessment (LCA) is a method used to study the environmental impact of a product or system across its entire life, from raw material extraction to final disposal [1]. The method became formally recognized when the International Standard Organization released the ISO 14040 framework, which explains the four main steps of LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation [2]. Since then, LCA has become one of the most trusted tools for understanding the environmental performance of products, materials, and infrastructure systems, including those used in civil engineering [3].

Even though LCA is widely used, it still has some well-known weaknesses. Common issues include unclear system boundaries, inconsistent choice of functional units, and poor data

* Corresponding author: prasanna.s@uceou.edu

quality, all of which can affect the reliability of results [4]. These problems become more noticeable in large infrastructure projects, such as bridges, where the scale of material use and construction activity is very high, and good quality data is often hard to find [5].

For construction-related studies, most researchers rely on process-based LCA (PLCA), which builds a picture of environmental impact from the bottom up by tracking material and energy flows through each stage of a process. Although this method gives detailed results, it can suffer from truncation errors caused by narrow system boundaries. To reduce this weakness, some studies combine PLCA with input-output based methods to form hybrid LCA (HLCA), which improves accuracy while keeping the detail needed for engineering applications [8]. A review of these hybrid inventory methods shows that the choice between process-based and hybrid approaches often depends on the size of the project and the data that is available [9].

Dynamic and time-based LCA models have also become important for construction studies, since building materials and structures interact with their environment differently over time. A review of dynamic modelling approaches noted that the research status of dynamic LCA is still developing, especially regarding how time-related data should be handled in impact assessment [6]. Similarly, a systematic review of dynamic variables used in building LCA studies found that most models still lack agreement on which time-dependent factors matter most [7]. Some studies have applied dynamic LCA directly to construction materials; for example, one study built a dynamic carbon and energy analysis model for cross-laminated timber, showing how emissions and energy use change across different life stages of a building material [11]. Other researchers have combined LCA with multi-criteria decision analysis to judge the impact of buildings on energy use, environmental damage, water use, and human health together, rather than looking at each factor separately [10].

Because full LCA studies can be costly, slow, and difficult to carry out with limited resources, many researchers have looked for ways to simplify the process without losing important accuracy. One such study focused specifically on how building LCA can be streamlined using partly simplified data and smart data collection methods, while still keeping the results reliable enough for decision-making [12]. This is especially relevant for bridge case studies, where full data collection for every material and process stage is often not practical.

To support a more complete environmental and economic picture, LCA is often paired with life cycle costing (LCC), which looks at the costs involved across the entire life of a product or structure. This combination helps decision-makers weigh environmental performance against financial factors together [13]. In terms of impact assessment methods, tools such as IMPACT World+ have been developed to bring together several older impact assessment methods into one consistent, globally applicable framework, and such methods are commonly available in LCA software including OpenLCA [14].

Finally, LCA has proven useful for a wide range of infrastructure and engineering systems beyond buildings, showing how the method adapts to different sectors. For example, one comprehensive assessment of greenhouse gas emissions from onshore wind energy infrastructure in China used simplified engineering-based models built on key design parameters, showing how large infrastructure systems can be analyzed even with incomplete data [15]. The current work addresses the gap by performing a detailed LCA of a concrete bridge using OpenLCA software. The analysis quantifies the environmental impacts of various bridge materials and components during the construction phase, employing ReCiPe Midpoint (H), Eco-Indicator 99, and Ecological Footprint categories. By emphasizing the relative contributions of different materials and structural elements, the present study provides insights into the environmental impacts of various materials, thereby providing an opportunity for the decison makers to use materials of low impacts.

2 Methodology

The present study adopts a LCA framework to calculate the environmental impacts associated with the construction phase of a concrete bridge located in Hyderabad, India. The methodology follows ISO 14040/44 standards for LCA and is implemented using Open LCA software, with datasets taken from the Ecoinvent v3.9.1 database. The assessment has four phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

2.1 Goal and Scope Definition

The main objective is to quantify the environmental impacts arising only from the material purchasing and construction of the bridge. The scope is limited to structural components viz. foundation, piers, abutments, deck slabs, approach slabs, crash barriers, wearing coats, and return walls and related construction materials. Labor activities, equipment manufacturing, worker transportation, maintenance, and demolition stages are not included. The functional unit is defined as the complete bridge structure spanning a 28.5 km road section between Velma Thanda and Tangedpally X Road.

2.2 Life Cycle Inventory (LCI)

The LCI involves gathering detailed information on material quantities used in each bridge component. Materials include cement, sand, aggregates, and reinforced steel, as these are the primary contributors during the construction stage. Material quantities were obtained from actual project records. Data was modelled in Open LCA using corresponding datasets from Ecoinvent, covering all upstream processes from raw material extraction to delivery at the construction site.

2.3 Life Cycle Impact Assessment (LCIA)

Environmental impacts were quantified using three recognized LCIA methods:
ReCiPe Midpoint v1.03 (H) – assessing midpoint indicators such as ecotoxicity, fossil fuel depletion, particulate matter formation, and water use.
Eco-Indicator 99 – evaluating endpoint categories including global warming potential, acidification, eutrophication, human toxicity, and resource depletion.
Ecological Footprint Analysis – estimating the land area required to offset CO_2 emissions generated during construction.
Each material and component used in the bridge was analysed for its contribution to these impacts, allowing the identification of the most environmentally harsh elements within the construction stage.

2.4 Life Cycle Impact Assessment (LCIA)

The LCIA results were interpreted to identify materials of high environmental impact and structural components during construction stage. Comparative analysis among different components highlighted variations in environmental impacts, and recommendations were made for reducing the impacts (Table 1). Approaches considered include the replacement of high-emission materials, such as cement, with supplementary cementitious materials, and the use of locally available aggregates to reduce emissions due to transportation of materials.

Table 1. Environmental impacts considered for the study

Eco-Indicator	ReCiPe Mid-Point (H)	Ecological Footprint
Eutrophication (EU)	Particulate Matter (PM)	Carbon Footprint (CFP)
Ozone Layer Depletion (OLD)		
Photochemical Oxidation (PC)	Ecotoxicity Fresh Water (EFW)	
Carcinogenic (HT-C)		
Global Warming (GW)	Fossil Fuel (FF)	
Acidification (AC)		
Non-Carcinogenic (HT-NC)	Water Use (WU)	
Mineral Resource (MR)		

3 Results and Discussions

The environmental impacts of bridge's construction phase were calculated using the ReCiPe Midpoint (H), Eco-Indicator 99, and Ecological Footprint methods. The results are presented in the following tables, showing the contributions of individual materials and structural components to key impact categories such as global warming potential, fossil fuel use, and resource depletion. These values highlight the relative environmental burden of each element, providing a basis for identifying high-impact targets for sustainable material substitution. Table 2 and Table 3 represent the environmental impact values of different LCIA methods considered in the study.

Table 2. Environmental impact values of materials using eco-indicator 99

Material	AC (Kg SO_2 eq)	GW (Kg CO_2 eq)	EU (Kg PO_4 eq)	OLD (Kg CFC eq)	HT-C (Kg 1,4-DCB eq)	HT-NC (Kg 1,4-DCB eq)	MR (Kg Cu eq)	PC (Kg C_2H_2)
Cement	20118	6817066	1408	0.28715	13930	334701	701128	9169
Sand	4720	126884	516	0.0019	1584	100206	57246	724
Aggregate	4510	91519	653	0.00102	4069	92339	63634	539
Reinforced Steel	10215	3E+06	2E+05	0.136	12429	3E+05	1E+05	7854

Table 3. Environmental impact values of materials using recipe mid-point and ecological footprint

Material	Recipe Mid-Point				Ecological Footprint
	EFW (Kg 1,4-DCB-Eq)	FF (MJ)	PM (Kg PM2.5 eq)	WU (m^3)	CFP (m^2a)

Cement	87609	806355	798	546	10105721
Sand	33588	41741	181	184	309251
Aggregate	44186	25611	219	429	225669
Reinforced Steel	37336	785618	578	480	8141180

The environmental impact results from the construction phase show significant variations between materials and impact categories across the three LCIA methods viz. Eco-Indicator 99, ReCiPe Midpoint (H), and Ecological Footprint.

a. Eco-Indicator 99 Insights

Table 2 show that the cement dominates in global warming potential (6.82×10^6 kg CO_2 eq), followed by reinforced steel (3×10^6 kg CO_2 eq). Cement's contribution is consistently high across acidification, carcinogenic, and mineral resource depletion indicators, mainly due to energy intensive clinker production and raw material extraction. Aggregates and sand show much lower impacts, with aggregate having slightly higher eutrophication potential than sand due to quarrying processes.

b. ReCiPe Midpoint (H) Results

Table 3 show that cement also has highest impact in fossil fuel use (806,355 MJ) and ecotoxicity freshwater (87,609 kg 1,4-DCB-Eq), representing its upstream energy requirements. Reinforced steel bars follow closely in fossil fuel use (785,618 MJ), accredited to ore extraction and smelting operations. Aggregates and sand record substantially lower values across all midpoint categories, supporting their relatively lower embodied environmental load.

c. Ecological Footprint Analysis

The Ecological Footprint results shown in Table 3 further confirm cement's supremacy in environmental impacts, showing the highest carbon footprint. Reinforced steel again holds the second highest position, while aggregates and sand remain comparatively small contributors.

d. Cross-Method Comparisons and Implications

All three LCIA methods have shown the same conclusion i.e. cement and reinforced steel are the highly impactful materials in the construction phase. This supports other LCA studies worldwide on concrete infrastructure, where high clinker content in cement and the energy requirements of steel production are responsible for high environmental impacts.

From a sustainability viewpoint, these findings highlight the importance of targeted material substitutions. Potential measures may include

- Reducing cement content by partial replacement with supplementary cementitious materials like fly ash, slag and silica fume.
- Usage of recycled steel to reduce fossil fuel and mineral resource depletion impacts.
- Procuring aggregates locally to cut transportation related emissions.

These strategies could significantly reduce the environmental footprint without compromising structural performance, aligning with sustainable construction goals and national carbon reduction commitments.

Table 4. Environmental impact values of components using eco-indicator 99

Bridge Components	AC (Kg SO_2 eq)	GW (Kg CO_2 eq)	EU (Kg PO_4 eq)	OLD (Kg CFC eq)	HT-C (Kg 1,4-DCB eq)	HT-NC (Kg 1,4-DCB eq)	MR (Kg Cu eq)	PC (Kg C_2H_2)
Foundation	5962	2008087	98954	0.06628	534171	2037152	57149	5073
Abutment	1425	475928	24518	0.0162	132158	497318	14156	1207
Pier	641	213989	11024	0.00728	59422	223606	6365	542
Return Wall	367	122531	6312	0.00417	34025	128038	3645	311
Deck Slab	4470	1515530	72038	0.0487	389363	1501495	41614	3819
Crash Barrier	204	67988	3503	0.00231	18879	71043	2022	172
Wearing Coat	131	44131	2175	0.00145	11739	44770	1256	111
ApproachSlab	66	17662	563	0.000518	17965	136649	2222	50

Table 5. Environmental impact values of components using recipe mid-point and ecological footprint

Bridge Components	Recipe Mid-Point				Ecological Footprint
	EFW (Kg 1,4-DCB-Eq)	FF (MJ)	PM (Kg PM2.5 eq)	WU (m^3)	CFP (m^2a)
Foundation	87609	431912	3136	8680	4846171
Abutment	33588	104651	758	2143	1144641
Pier	44186	47054	341	964	514657
Return Wall	37336	26943	195	552	294696
Deck Slab	128277	320300	2330	6337	3667215
Crash Barrier	6202	14950	108	306	163515

Wearing Coat	3863	9492	69	191	106502
Approach Slab	14378	4329	45	33	42591

The environmental impact assessment of bridge components during the construction phase evaluated using Eco-Indicator 99, ReCiPe Midpoint (H), and Ecological Footprint methods reveal significant changes in environmental burdens depending on structural function and material requirements.

a. Eco-Indicator 99 Observations

Table 4 shows that the foundation consistently has the highest environmental impact across all categories, with a global GW of 2,008,087 kg CO_2 eq, high AC (5962 kg SO_2 eq), and significant human toxicity of 534,171 kg 1,4-DCB eq. This is mainly due to the large mass of concrete and reinforced steel used in the bridge. The deck slab is the second-most impactful component, contributing greatly to GW (1,515,530 kg CO_2 eq) and mineral resource depletion, reflecting its large surface area and high cement and steel content.

In contrast, approach slabs, wearing coats and crash barriers show low impacts in most categories, mainly due to their smaller material demands. For example, the approach slab records only 17,662 kg CO_2 eq in GW and the lowest acidification value (66 kg SO_2 eq).

b. ReCiPe Midpoint (H) Results

Table 5 shows the maximum values for the foundation in fossil fuel use (431,912 MJ) and water use (8,680 m^3), with the deck slab again taking second place in these categories. Particulate matter emissions are highest for the foundation (3,136 kg $PM_{2.5}$ eq) and deck slab (2,330 kg $PM_{2.5}$ eq), due to the intensive production processes for cement and steel. Less impact components such as the approach slab and wearing coat remain consistent in their reduced contributions across these indicators.

c. Ecological Footprint Analysis

When expressed in CO_2 equivalent land area (m^2a), the foundation has the highest footprint (4,846,171 m^2a), followed by the deck slab (3,667,215 m^2a). The approach slab has the lowest footprint (42,591 m^2a), strengthening the link between material quantity and environmental burden.

d. Implications for Sustainable Construction

Across all three LCIA methods, the foundation and deck slab are the most environmentally burden components in the construction phase. Given their high cement and steel requirements, customized strategies for these components could have significant reductions in the bridge's overall environmental footprint. Possible measures may include optimizing structural design to reduce material usage without compromising on safety parameters. Substituting cement with supplementary cementitious materials (SCMs) like fly ash or slag to cut CO_2 emissions is also another viable option.

Using high recycled content steel to reduce fossil fuel consumption and resource depletion. Implementing low-carbon concrete mixes to further reduce embodied carbon. The consistently low impacts from smaller components (e.g., approach slab, wearing coat) indicate that environmental optimization efforts should be prioritized on high volume and high mass elements. This targeted approach can deliver substantial sustainability gains while maintaining structural integrity.

4 Conclusions

This study applied a Life Cycle Assessment (LCA) approach using Open LCA software and the Ecoinvent v3.9.1 database to quantify the environmental impacts of a concrete bridge in Hyderabad, focusing exclusively on the construction phase. Three LCIA methods viz. ReCiPe Midpoint v1.03 (H), Eco-Indicator 99, and Ecological Footprint—were employed to evaluate impacts at both the material and component levels.
The results showed that the cement and reinforced steel are the most environmentally burden materials, with cement contributing the highest global warming potential (6.82×10^6 kg CO_2 eq) due to its energy intensive clinker production, and reinforced steel showing substantial impacts in fossil fuel depletion and resource scarcity. Aggregates and sand, by contrast, recorded significantly lower impacts across all categories.
At the component level, the foundation and deck slab emerged as the most impactful elements in terms of carbon footrint, fossil fuel use, and water consumption, reflecting their large material volumes and reinforcement requirements. Smaller components, such as the approach slab and wearing coat, demonstrated minimal contributions to overall environmental burdens. These findings underscore the need for targeted mitigation strategies in high-impact materials and components. Recommandations include:

- Partial replacement of cement with supplementary cementitious materials (fly ash, slag, silica fume) to lower CO_2 emissions.
- Use of recycled or high-recycled-content steel to reduce embodied energy and resource depletion.
- Local sourcing of aggregates to minimize transportation-related impacts.
- Adoption of low-carbon concrete mixes and optimized structural design to reduce material demand without compromising performance.

By implementing these measures, significant reductions in the environmental footprint of bridge construction projects can be achieved, supporting broader sustainability goals and aligning national carbon reduction commitments.

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