Whole Life Civil Systems Analysis

Life-Cycle Assessment
Individual Project Assignment 2
Life-Cycle Analysis and Multi-Criteria Decision Making

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Table of Context

1. Introduction.. 3
2. Goal and Scope.. 3
3. Design Alternatives 4
4. Life Cycle Inventory 7
5. System Lifespan with Interventions.. 9
6. Life Cycle Inventory and Analysis...13
7. MCDM– Analytic hierarchy process (AHP)...15
8. REFERENCES 16

1. Introduction

In the dynamic landscape of modern transportation infrastructure, the selection of a railway bridge design holds profound implications for sustainability and efficiency. This report delves into the intricate realms of life cycle analysis and multi-criteria decision-making, with a specific focus on three distinct design alternatives. These alternatives involve prefabricated concrete girders with cast-in-place decks, steel girders with prefab concrete decks, and steel girders with fiber-reinforced polymer decks. Central to our exploration is the railway ballast—a critical component influencing track stability and, consequently, the overall performance of the bridge. The report endeavors to meticulously assess and compare the environmental impact, cost considerations, and long-term durability associated with each design option, with a nuanced emphasis on the type of ballast employed. As the transportation sector strives for sustainable solutions, this study aims to offer crucial insights, aiding decision-makers in selecting a design that optimally balances the complexities of construction, operation, and maintenance, with particular attention to the pivotal role played by the chosen ballast material.

2. Goal and Scope

The goal of this assessment is to conduct a comprehensive life cycle analysis and multi-criteria decision-making process for three railway bridge design options, each incorporating different materials and methodologies for the rail ballast. The primary objective is to evaluate the environmental, economic, and durability implications associated with the use of prefabricated concrete girders with cast-in-place decks, steel girders with prefab concrete decks, and steel girders with fiber-reinforced polymer decks, specifically focusing on the type of ballast employed in each case. The scope encompasses the entire life cycle, including the construction, operational, and maintenance phases. By scrutinizing the intricate interplay of design choices and ballast materials, this assessment aims to provide valuable insights for informed decision-making, contributing to the development of sustainable and resilient railway infrastructure.

3. Design Alternatives

The proposed railway bridge design options encompass three distinct alternatives. The first entails prefabricated concrete girders supporting a cast-in-place deck, accompanied by a conventional railway structure incorporating rails, wooden sleepers, and stone ballast. The second design features steel girders supporting a prefabricated concrete deck, with a similar railway configuration. The third alternative introduces innovation with steel girders and a fiber-reinforced polymer deck, coupled with a railway track comprising rails, wooden sleepers, and a concrete slab as ballast. These design variations present diverse approaches to structural composition and material utilization, emphasizing the critical role of the chosen ballast material in track stability and, consequently, overall bridge performance.

Design option	Girders Material	Deck Material	Rail Material	Sleeper Material	Ballast Material
Option 1	Prefab concrete	Cast in place concrete	Hot Rolled Steel	Wood	Stone
Option 2	Steel	Prefab concrete elements	Hot Rolled Steel	Wood	Stone
Option 3	Steel	Fiber-reinforced polymer	Hot Rolled Steel	Wood	Concrete Slab as Ballast

Table 1: Design Options

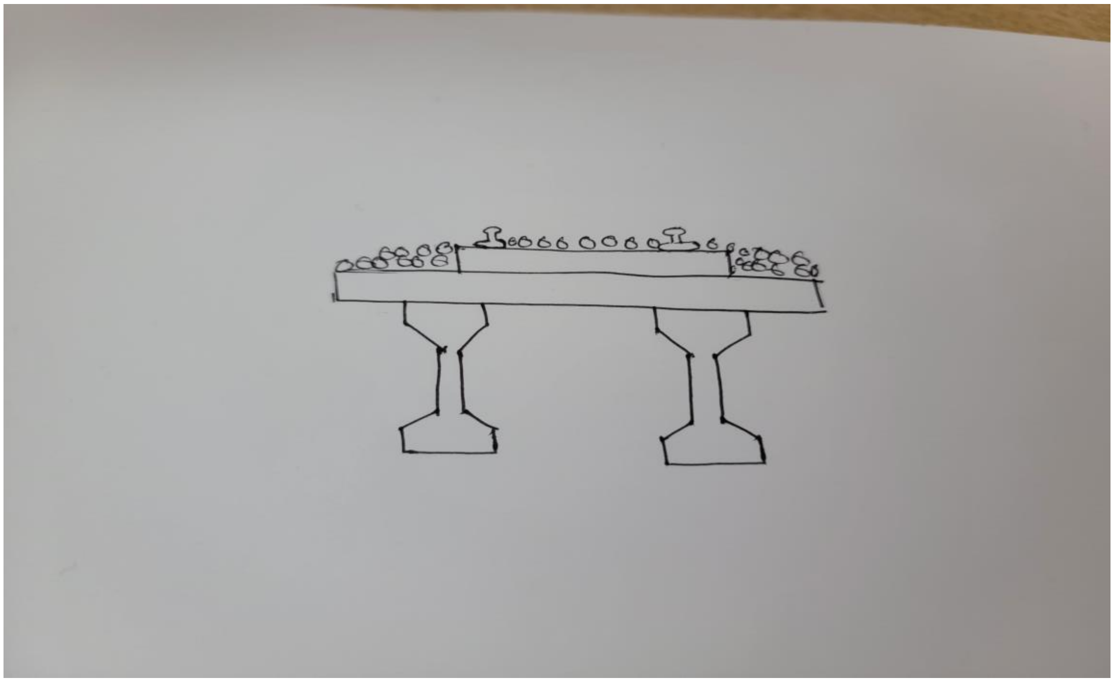


Figure 1: Traditional ballasted track, wooden sleeper with prefab concrete girder and cast in place deck

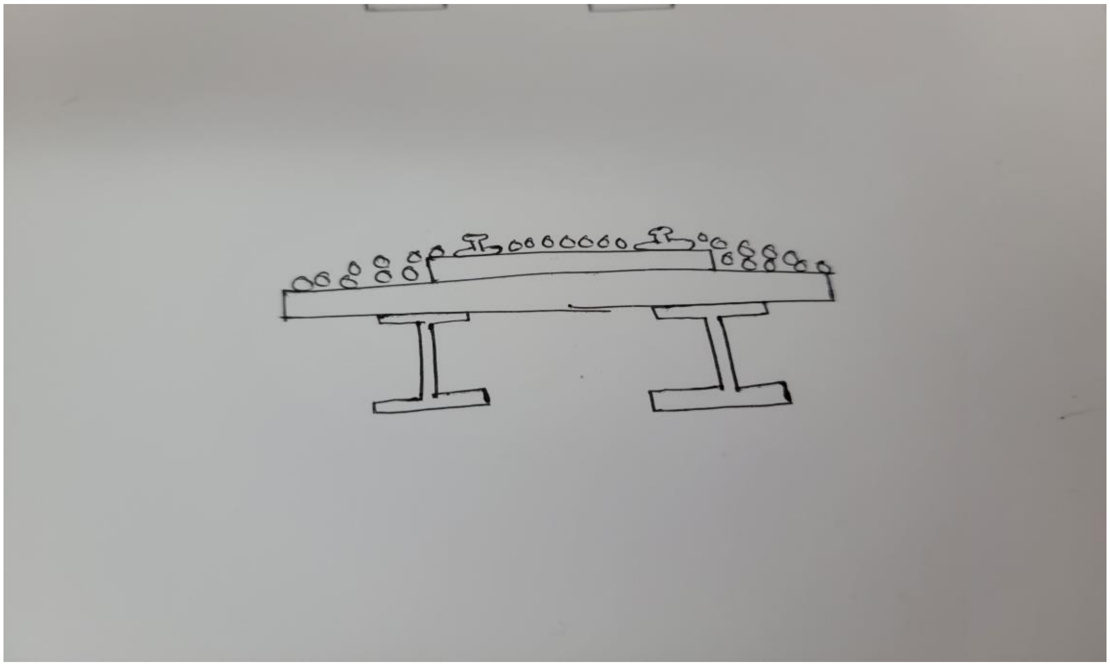


Figure 2: Traditional ballasted track, wooden sleeper with steel girder and prefab concrete deck

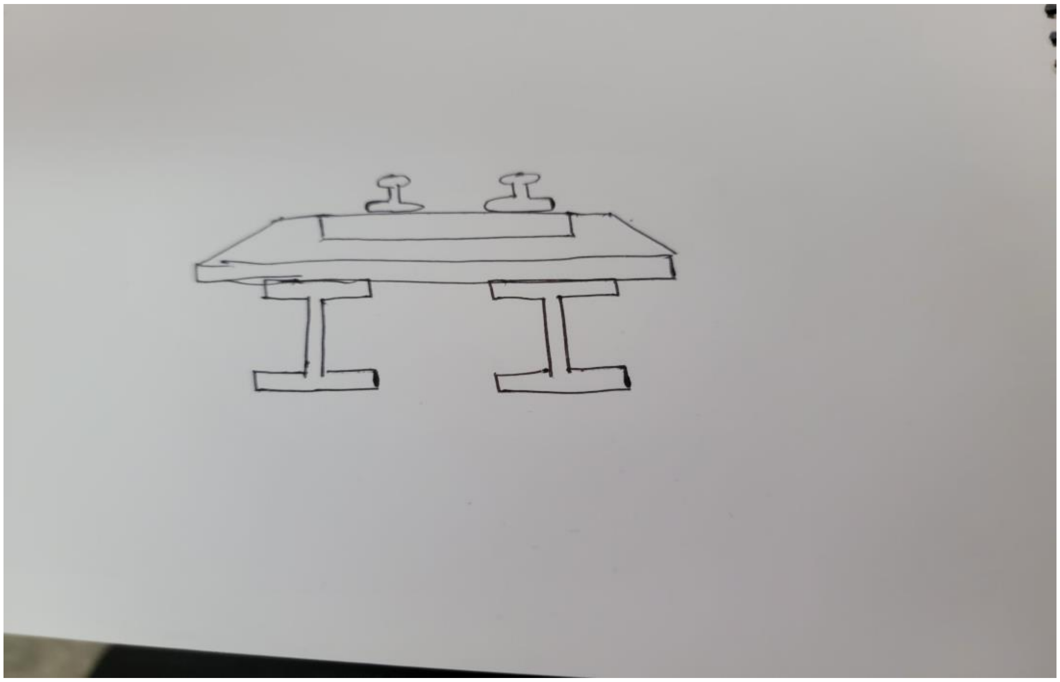


Figure 3: Rail track, wooden sleeper, concrete slab placed as subgrade with steel girder and fiber-reinforced polymer deck

Element	**Cross Section Area (m2)**	**Material**
Prefab concrete girder	0.78	50MPa, mix 1 (Marceau, 2007)
Steel girder (HEM800 – 317kg/m)	0.04043	S355J0WP
Deck (width = 15m, thickness = 0.25m)	3.75	20MPa, mix 5 (Marceau, 2007)
Prefab deck	0.5 * Deck	50MPa, mix 1 (Marceau, 2007)
Fiber-Reinforced Polymer	0.2* Deck	Fiber-reinforced Polymer

Rail	0.0258	Hot rolled steel I-section
Sleeper	0.00104	Wood
Stone	0.5 * Deck	Crushed Stone
Concrete slab as Subgrade	1.92	50MPa, mix 1 (Marceau, 2007)

Table 2: Different set of elements that accompany material specifications and cross-sectional areas.

4. Life Cycle Inventory of different materials, Performance, and environmental indicators

The following table presents the composition of different materials used. For each material, we collected information about energy consumption for fabrication and processing (MJ/t), CO2, NOX, SO2 (kg/m3) and cost associated with extraction, processing, manufacture, and construction.

Material	**scope**	**Quantities**	**Energy**	**CO2**	**NOX**	**SO2**
Cement	Reinforced Concrete	217	3.26	0.822	0.177	0.065
Fly Ash	Reinforced Concrete	78	0	0.0025	0	0.78
Coarse Aggregates	Reinforced Concrete	1583	0.0035	0.016	0.0018	0.0018

Fine Aggregates	Reinforced Concrete	1256	0.0023	0.0053	0.009	0.009
Reinforcement	Reinforced Concrete	208	2430	225	0.71	1.85
Steel	Steel	1	2430	225	0.71	1.85
FRP	Fiber-reinforced Polymer	1	169.69	3.09	0.766	0.036
Cement	Precast reinforced concrete	753	3.26	0.822	0.177	0.065
Coarse Aggregates	Precast reinforced concrete	1578	0.035	0.016	0.0018	0.0018
Fine Aggregates	Precast reinforced concrete	777	0.0023	0.0053	0.009	0.009
Reinforcement Girders	Precast reinforced concrete.	367	2430	225	0.71	1.85
Hot Rolled Steel	Railway	30	2430	225	0.71	1.85
Wood	Sleeper	165	1240	225	0.177	1.85
Stone	Ballast	102	0.035	0.016	0.0018	0.0018

Table 3: Materials with Performance and Environmental indicators

The “quantities” column has a different meaning, depending on the materials. For Reinforced Concrete and Precast reinforced concrete those are the quantities of materials consumed to produce a cubic meter of concrete, respectively the reinforcement in Kg usually used for 1cubic meter of concrete. For steel and Fiber-reinforced Polymer is indicated 1, because the energy consumed as well as the emissions are indicated for each Kg of materials produced and consumed. For Hot Rolled Steel and wooden sleeper which is used as rail track has the total quantity required for the bridge. The stone is calculated in cubic meter.

5. System Lifespan with Interventions

The lifespan of typical Railway Bridge is around 120 years. During this lifetime, there are several maintenance and repair events that the total system may need to undergo. For the three design options there are some frequent interventions and some replacement activities take place. The interventions are summarized in the following table:

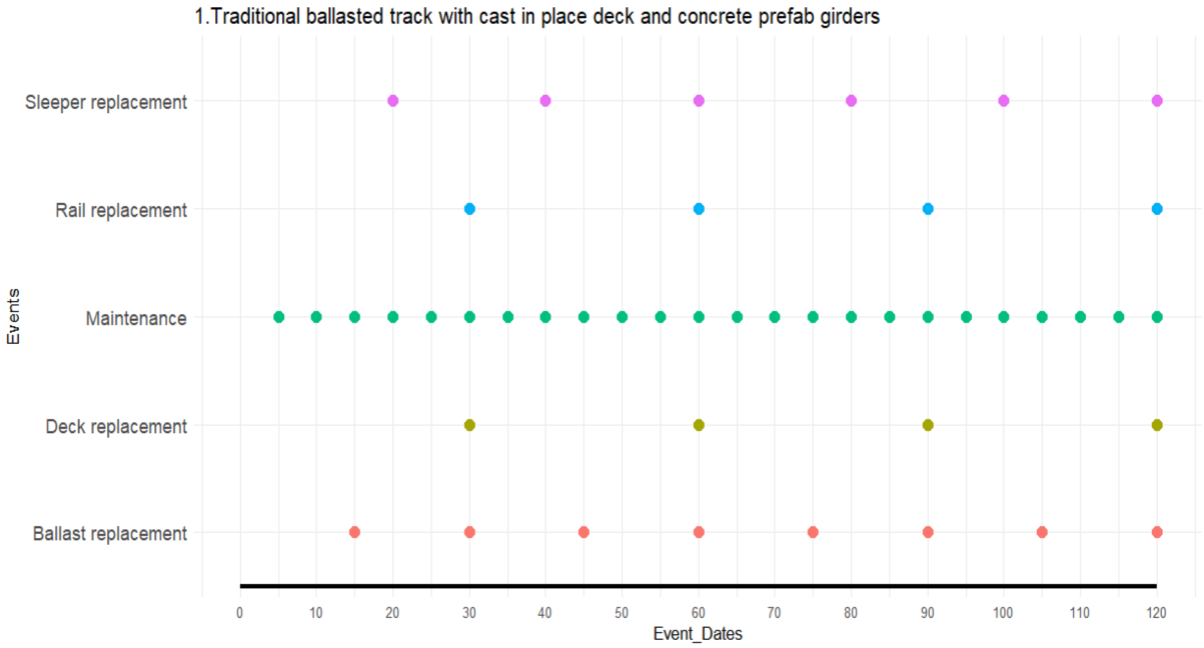
Design Options	Event	Frequency	Total Lifespan
1.Traditional ballasted track with cast in place deck and concrete prefab girders	Maintenance	5	120
1.Traditional ballasted track with cast in place deck and concrete prefab girders	Deck replacement	30	120
1.Traditional ballasted track with cast in place deck and concrete prefab girders	Ballast replacement	15	120

1.Traditional ballasted track with cast in place deck and concrete prefab girders	Sleeper replacement	20	120
1.Traditional ballasted track with cast in place deck and concrete prefab girders	Rail replacement	30	120
2.Traditional ballasted track with prefab deck and steel girders	Maintenance	5	120
2.Traditional ballasted track with prefab deck and steel girders	Deck replacement	30	120
2.Traditional ballasted track with prefab deck and steel girders	Ballast replacement	15	120
2.Traditional ballasted track with prefab deck and steel girders	Sleeper replacement	20	120
2.Traditional ballasted track with prefab deck and steel girders	Rail replacement	30	120
2.Traditional ballasted track with prefab deck and steel girders	Partial replacement	45	120
3.Concrete slab placed as elastic subgrade with FRP deck and steel girder	Maintenance	5	120
3.Concrete slab placed as elastic subgrade with FRP deck and steel girder	Deck replacement	30	120
3.Concrete slab placed as elastic subgrade with FRP deck and steel girder	Sleeper replacement	20	120

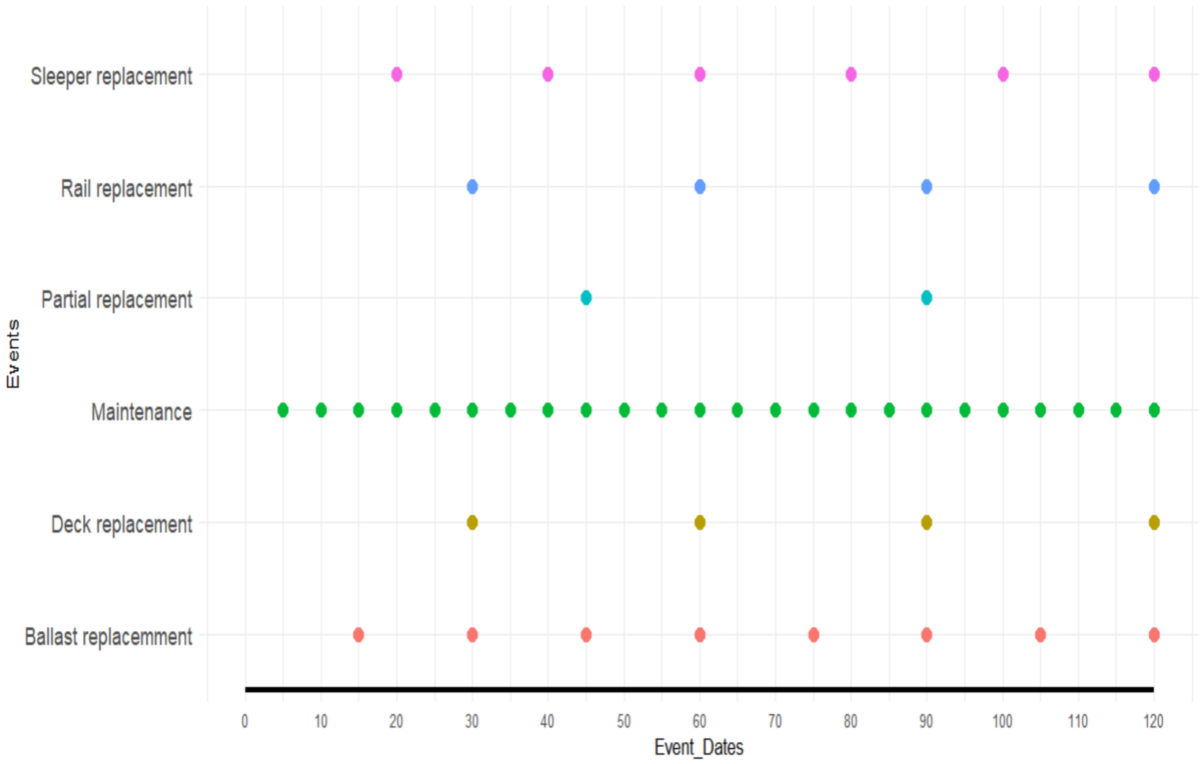
3.Concrete slab placed as elastic subgrade with FRP deck and steel girder	Rail replacement	30	120
3.Concrete slab placed as elastic subgrade with FRP deck and steel girder	Subgrade replacement	25	120

Table 4: Design options, interventions and their frequencies

We can plot these interventions on timelines specific to each design option, so that maintenance or repairs can be planned accordingly. Major interventions can be combined, to minimize mobilization and time costs. Using the Shiny app the needed interventions for each design option over its lifetime from Table 4 are being visualized below.



2.Traditional ballasted track with prefab deck and steel girders



3.Concrete slab placed as elastic subgrade with FRP deck and steel girder

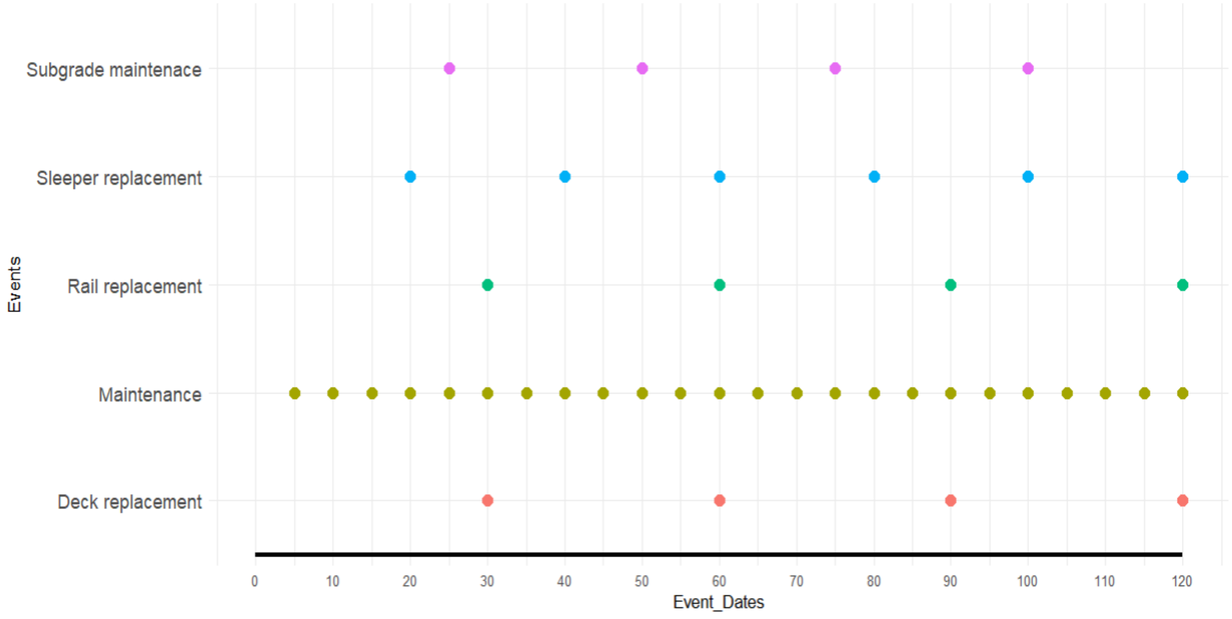


Figure 4: Visualization of design option specific interventions from Shiny app

6. Life Cycle Inventory and Analysis

The results of the Life Cycle Inventory Analysis were computed using R, which facilitated the determination of material quantities for each design options and the total material needed for every design option. Subsequently, the environmental indicators were applied to calculate the corresponding environmental impacts for each option. The findings are presented in the following bar plots.

Figure 5: CO2 emissions for eacjh design options

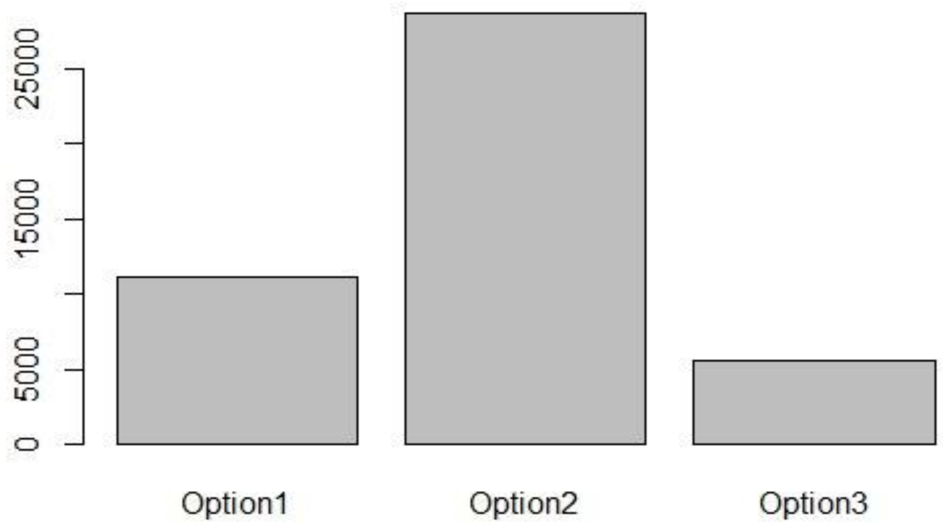


Figure 6: SO2 emissions for each design options

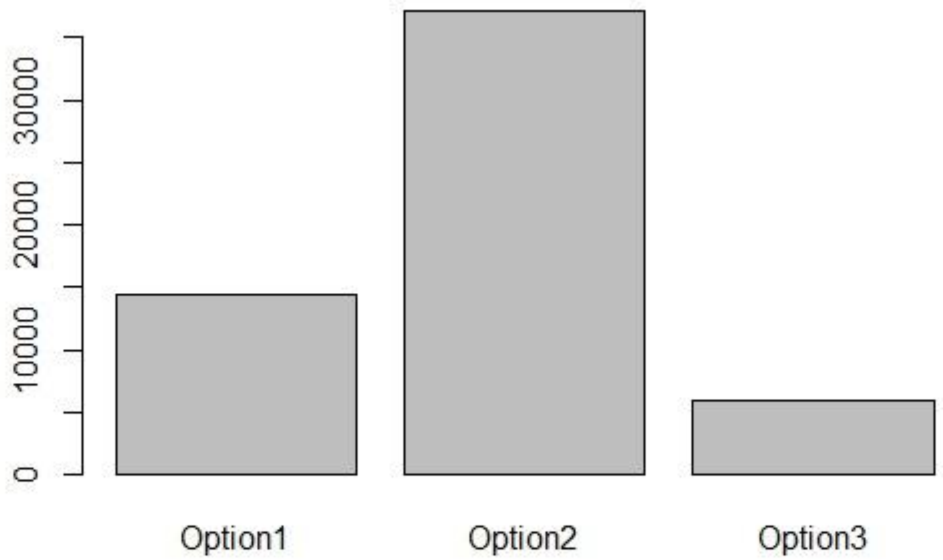


Figure 7: NOX emissions for each design options

The environmental indicator that exhibits the most variation among the three design options is carbon emissions. Option 3 has the lowest, possibly influenced by the bio-chemical behavior of concrete slab replacing the stone over its lifetime and the very less amount of repair required. Similarly, Option 3 shows the lowest SO2 and NOX emissions. Energy consumption is comparable across all three options. The most even distribution of emissions is observed in design Option 3. Based on these plots alone, it becomes evident that achieving the goal of ranking the options based on ecological emissions depends on the weighting of the categories. This aspect will be further investigated using a Multi-Criteria Decision-Making method.

7. MCDM – Analytic hierarchy process (AHP)

In the previous section we analyzed the values for each of the environmental indicators independently. This is while in reality we need to see and analyze the effects of all the influential effects together to be able to make informed decisions. To achieve this, in the final section, we establish the analytic hierarchy process (AHP) to see the integrated effect of all our multi criteria based on their importance. Figure 8, represents the result of the multi criteria decision making process. It can be clearly seen that option number 2 which has the highest score with nearly 41%, followed by the other design option with 31.2 %. Option 1 has the lowest score standing less than 29. It seems that option 1 and 3 are very close.

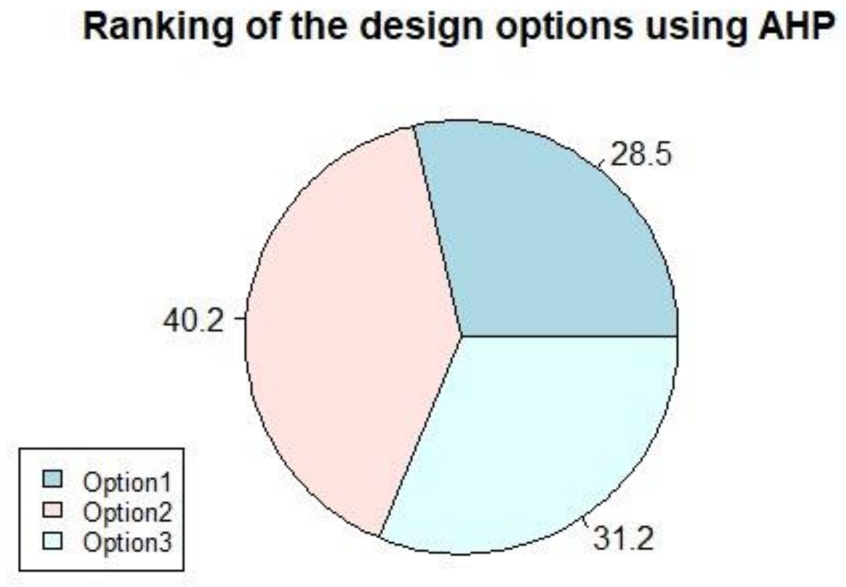


Figure 8: AHP results

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