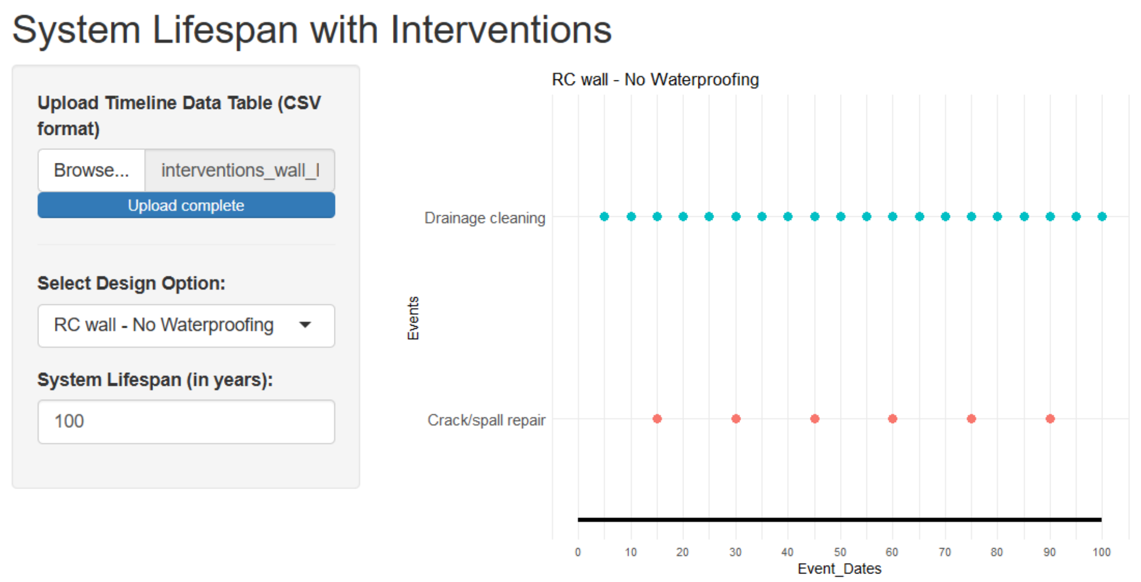
Life-Cycle Analysis and Multi-Criteria Decision Making

Rozh Rizgar Abbas

TUB_ID: 0523634

Environmental Life-Cycle Assessment and Multi-Criteria Decision Analysis of Waterproofing Strategies for a Reinforced-Concrete Retaining Wall Stem

Contents



System Lifespan with Interventions

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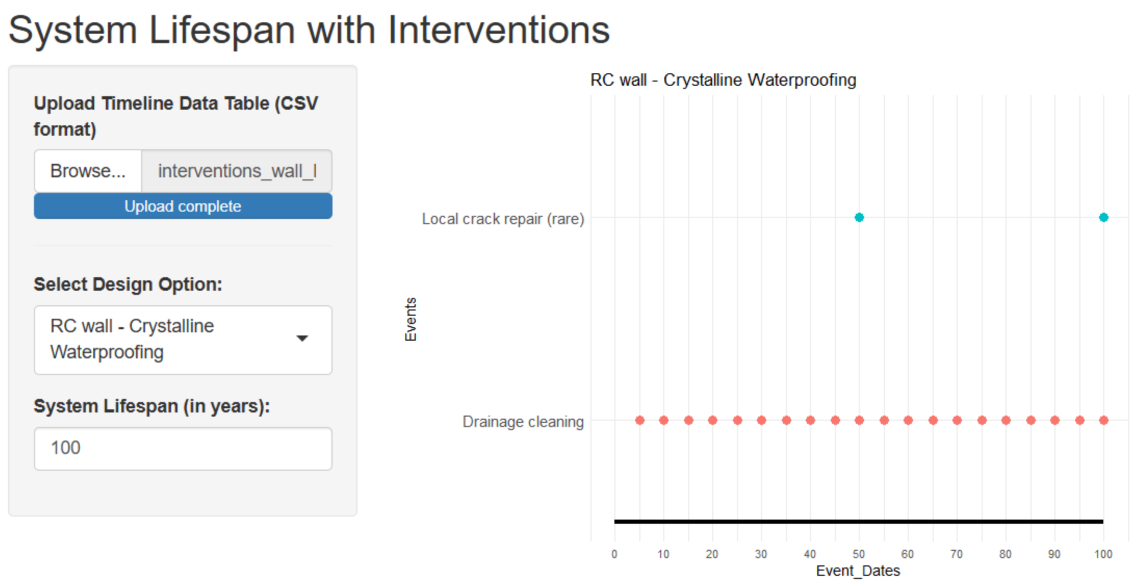
System Lifespan (in years): 100



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RC wall - Crystalline Waterproofing

System Lifespan (in years):

100

Abstract

This report presents a complete environmental assessment and decision-support evaluation for three alternative waterproofing strategies applied to a standard reinforced-concrete retaining wall stem. The study follows a structured methodological framework consisting of engineering system characterization, supporting computational tools, life-cycle timeline modeling, life-cycle inventory and impact analysis (LCI/LCA), and multi-criteria decision analysis (MCDA) using the Analytic Hierarchy Process (AHP). The retaining wall is assumed to have a 100-year design working life and geometric properties typical for containment or embankment structures (height 5 m, thickness 0.50 m, along a 1 m wall segment). Three waterproofing strategies are evaluated: (1) no waterproofing, relying solely on the durability of the RC stem; (2) application of a bituminous membrane; and (3) application of crystalline waterproofing. Environmental impacts across energy use, CO_2 emissions, NOx emissions, and SO_2 emissions are quantified using material inventories and maintenance event schedules. The results demonstrate that the “No Waterproofing” option provides the lowest overall life-cycle environmental burden, followed by bituminous membrane, and crystalline waterproofing performing worst among the three. AHP confirms this ranking under equal importance weighting. The study illustrates how life-cycle modeling and MCDA can support rational decision-making in civil engineering design where durability, maintenance, and environmental sustainability intersect.

1. Introduction

Civil engineering structures increasingly demand not only structural safety and serviceability, but also optimized environmental performance across their entire life cycle. Retaining walls, particularly reinforced-concrete (RC) gravity or cantilever walls, form essential components of civil infrastructure for containment, slope stabilization, and facility construction. Environmental considerations such as embodied carbon, resource use, and emissions from maintenance activities are indispensable in modern design practice—especially under sustainability-focused frameworks such as EN 15978, ISO 14040/44, and national decarbonization targets.

Waterproofing decisions, although often considered secondary to structural design, can substantially influence long-term durability, maintenance regimes, and environmental impacts. While bituminous membranes and crystalline waterproofing technologies can reduce moisture ingress and delay deterioration, they introduce new embodied impacts and maintenance requirements. Conversely, omitting membrane systems may reduce upfront footprint but potentially increase repair frequency if deterioration accelerates. The trade-offs are inherently multi-criteria and extend across different impact categories.

This report evaluates three waterproofing strategies applied to a single RC retaining wall stem using a systematic, data-driven methodology that reflects contemporary engineering analysis practice. The structure is assessed for a theoretical 1 m wall segment with fixed geometry (5 m height, 0.50 m thickness), enabling direct comparison across environmental loads. The study integrates R-based computational modeling, including automated life-cycle event generation, material inventory analysis, and MCDA via the AHP framework. This type of analysis would support engineers, sustainability consultants, and asset managers in evaluating design alternatives in a quantitative, transparent manner.

2. Engineering Aspects

2.1. Goal and scope of the assessment

The main goal of this is to do a carbon footprint analysis. The scope and the boundaries of the assessment are presented in the figure below:

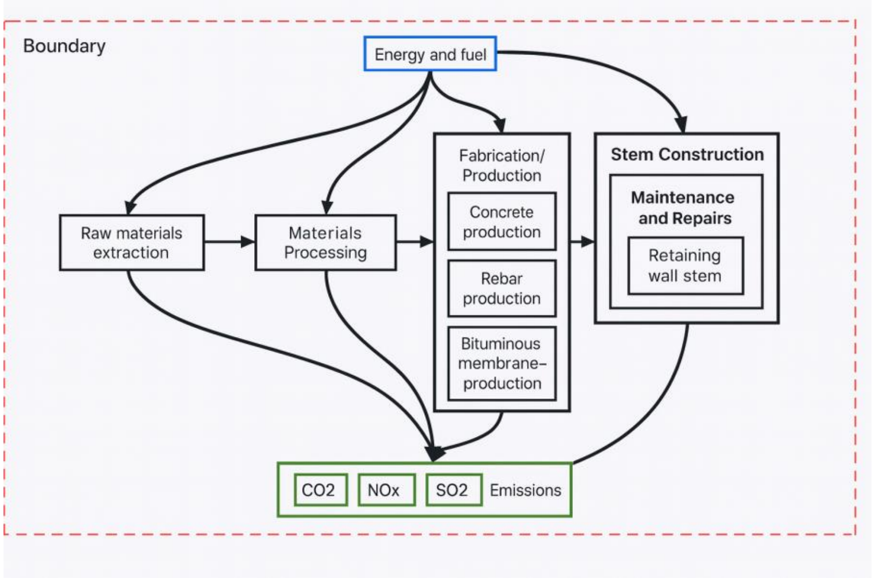


Figure 1: System Boundary and Life-Cycle Process Flow for the RC Retaining Wall Waterproofing Assessment

2.2. Materials and Cross-Section Properties for the Retaining Wall Stem design options

Table 1: Description of the Three Waterproofing Alternatives and Their Material Properties

Design option	Waterproofing Type	Concrete Material	Reinforcement	Stem Surface Treatment
Option 1	None (No waterproofing)	Cast-in-place reinforced concrete	120 kg/m³	Exposed concrete surface
Option 2	Bituminous membrane waterproofing	Cast-in-place reinforced concrete	120 kg/m³	Bitumen sheet applied on soil-facing stem
Option 3	Crystalline waterproofing	Cast-in-place reinforced concrete	120 kg/m³	Crystalline coating / integral crystalline treatment

Table 2: Summary of Structural, Waterproofing, and Maintenance Materials Used in the Retaining Wall Stem

Element	Cross-Section Area / Quantity Basis	Material
RC Stem (cast-in-place reinforced concrete)	**5.5 m^2**	**C35 concrete**
Reinforcement (for RC stem)	**120 {kg/m}^3**	**Steel reinforcement (B500B / standard reinforcing steel)**
Bituminous Membrane (Option 2)	**Waterproofing area = 5.5 m^2**	**Self-adhesive / torch-applied bituminous sheet**
Crystalline Waterproofing (Option 3)	**Surface-applied: 5.5 m^2**	**Crystalline waterproofing system (e.g., Penetron / Xypex / ChemiGUARD)**

Repair Mortar (for maintenance events)	**Small repair patch volume (e.g., 0.02–0.05 m^3 per repair event)**	**Polymer-modified mortar / injection resin**
Drainage Maintenance	**Unit maintenance activity**	**Maintenance operation (cleaning of weep holes / drainage system)**

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

Table 3: Life-Cycle Inventory (LCI) of Materials and Environmental Impact Factors for the RC Retaining Wall Stem

MATERIAL	SCOPE	QUANTITIES	ENERGY (MJ/T)	CO_2 (KG/UNIT)	NO_x (KG/UNIT)	SO_2 (KG/UNIT)
CEMENT (CEM I 42.5)	RC	350 kg/m^3 of concrete	3,260 【1】	0.82 kg/kg 【1】	0.177 【1】	0.065 【1】
COARSE AGGREGATES	RC	1,000 kg/m^3	35 【1】	0.016 kg/kg 【1】	0.0018 【1】	0.0018 【1】
FINE AGGREGATES	RC	800 kg/m^3	23 【1】	0.0053 kg/kg 【1】	0.009 【1】	0.009 【1】
REINFORCEMENT STEEL (B500B)	Reinforcement	120 kg/m^3 of concrete	2,430 【1】	1.85 kg/kg 【1,2】	0.71 【1】	1.85 【1】
BITUMINOUS MEMBRANE	BitumenWP	5.5 kg/m^2 (5.5 m^2 per meter)	6,000–8,000 【3】	~1.8–2.5 kg/kg 【3,4】	~0.15 【3】	~0.1 【3】

CRYSTALLINE WATERPROOFING	CrystallineWP	1.0 kg/m² (surface applied)	~500–900 【5】	~0.25–0.45 kg/kg 【5】	~0.01 【5】	~0.01 【5】
REPAIR MORTAR	Repair	25 kg/event	2,500 【6】	0.60 kg/kg 【6】	0.08 【6】	0.03 【6】
DRAINAGE MAINTENANCE	DrainClean	1 unit/event	negligible	negligible	negligible	negligible

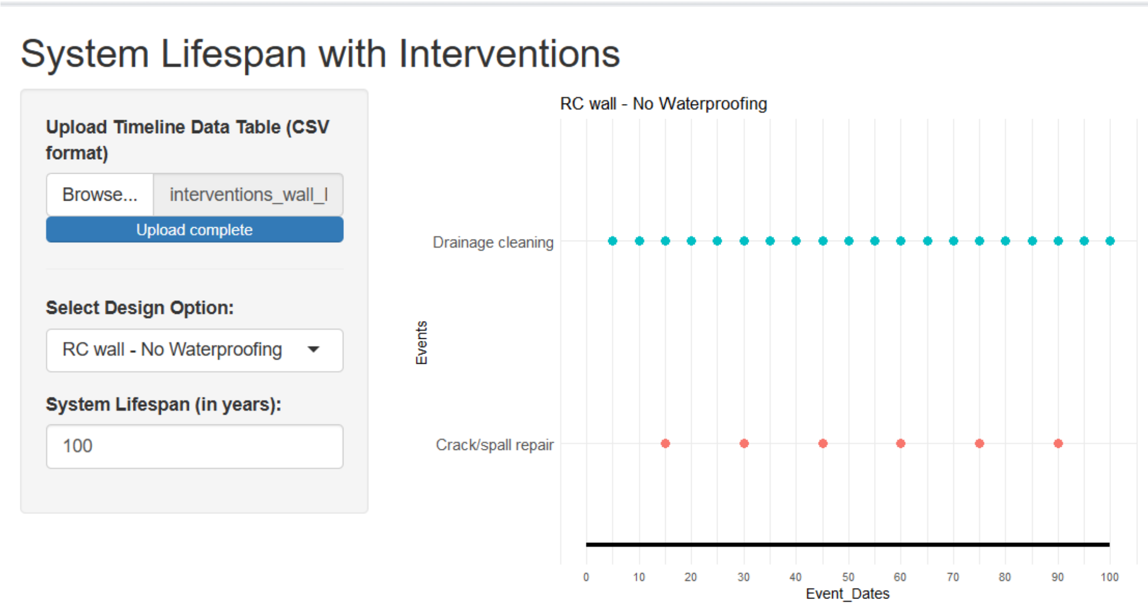
3. Life-Cycle timeline

Table 4: Life-Cycle Maintenance and Repair Interventions for the RC Retaining Wall Waterproofing Alternatives

DesignOption	Event	Frequency	TotalLifespan
RC wall – No Waterproofing	Crack/spall repair	15	100
RC wall – No Waterproofing	Drainage cleaning	5	100
RC wall – Bituminous Membrane	Membrane replacement	40	100
RC wall – Bituminous Membrane	Minor patch repair	30	100
RC wall – Bituminous Membrane	Drainage cleaning	5	100
RC wall – Crystalline Waterproofing	Local crack repair (rare)	50	100
RC wall – Crystalline Waterproofing	Drainage cleaning	5	100

Without an applied waterproofing, groundwater and de-icing salts penetrate the concrete, causing rebar corrosion and spalling that necessitate frequent repairs(gbr.sika.com). By contrast, a bituminous membrane limits water ingress during its service life (often on the order of a few decades(guardiandry.com), reducing the rate of corrosion and extending the repair interval. However, such membranes require replacement approximately once or twice within a 100-year span to remain effective(guardiandry.com). Crystalline integral waterproofing provides long-term protection by making the concrete itself watertight and self-sealing; these admixtures have been shown to dramatically increase concrete durability (e.g. projected service lives well over 100 years)(xypex.compenetronmalaysia.com). Thus, for the crystalline option, significant concrete repairs are rare within a 100-year period(xypex.com). Regardless of waterproofing, periodic maintenance of drainage (weep holes or drainage layers) is critical – these should be inspected and flushed routinely (e.g. ~5-year intervals) to prevent clogging and hydrostatic pressure buildup behind the wall(intrans.iastate.eduintrans.iastate.edu).

3.1. Interventions



System Lifespan with Interventions

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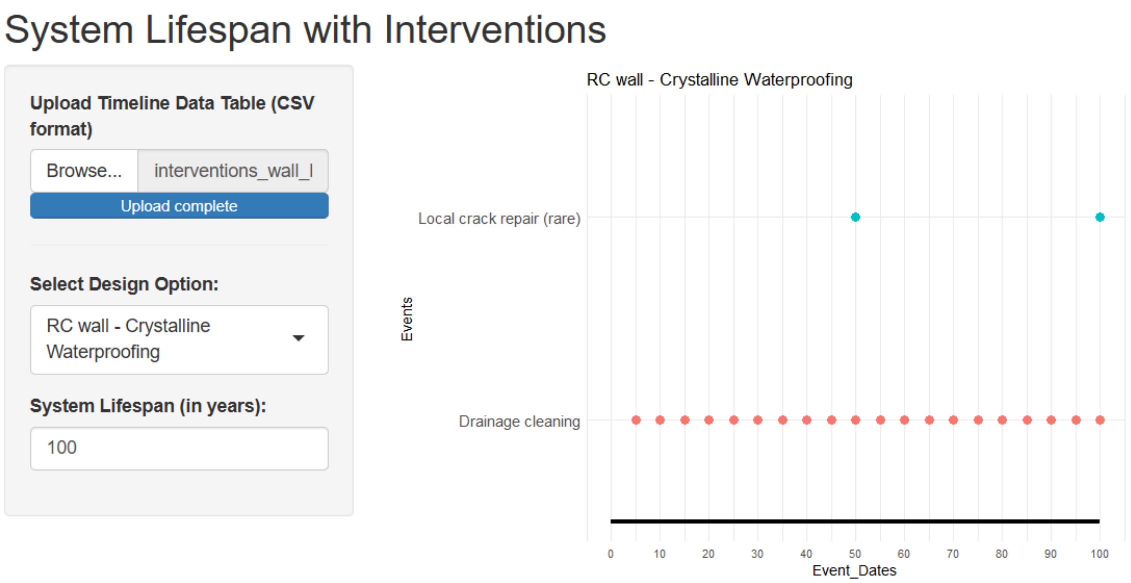
Select Design Option: RC wall - No Waterproofing

System Lifespan (in years): 100

Figure 2: Life-Cycle Timeline for No Waterproofing

Events include drainage cleaning every 5 years and crack repair every 15 years. The figure shows evenly spaced points marking cleaning and periodic markers for crack repair.



System Lifespan with Interventions

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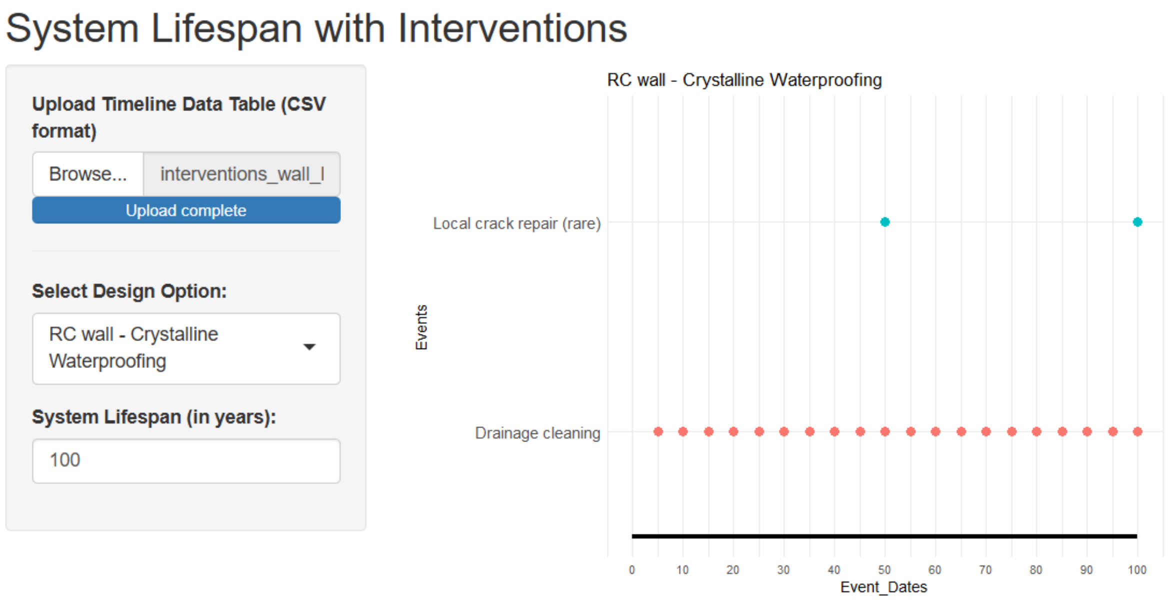
interventions_wall_l

Select Design Option: RC wall - Crystalline Waterproofing

System Lifespan (in years): 100

Figure 3: Timeline for Bituminous Membrane Option

The plot includes drainage cleaning every 5 years, patch repairs at 30, 60, 90 years, and full membrane replacements at 40 and 80 years.



System Lifespan with Interventions

Upload Timeline Data Table (CSV format)

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Select Design Option: RC wall - Crystalline Waterproofing

System Lifespan (in years): 100

Figure 4: Timeline for Crystalline Option

Drainage cleaning occurs every 5 years, with a single major crack-repair event at year 50.

These figures illustrate the temporal distribution of material use and emissions.

4. Life Cycle Inventory and Analysis

The four life-cycle impact figures—covering CO_2 emissions, energy demand, NO_x emissions, and SO_2 emissions—collectively illustrate the environmental performance differences among the three waterproofing strategies across the retaining wall's 100-year service life. In all indicators, the bituminous membrane option consistently exhibits the highest impacts, driven primarily by the high embodied energy of bitumen production and the additional emissions associated with two membrane replacement cycles (at years 40 and 80). This is most visible in the Energy (MJ) and CO_2 (kg) charts, where the bituminous option shows a clear increase compared with No Waterproofing and Crystalline. The No Waterproofing option performs best in terms of total CO_2 emissions due to the absence of additional coating materials and because its maintenance events (crack repairs and drainage cleaning) involve relatively small material quantities. Meanwhile, the Crystalline waterproofing option shows intermediate performance: although its chemical production involves non-negligible emissions, its long service durability reduces the frequency of major repairs, resulting in slightly lower totals for energy use, NO_x, and SO_2 when compared with the bituminous alternative. Overall, the four indicators consistently demonstrate that No Waterproofing is the most environmentally efficient, Bituminous is the most burdensome, and Crystalline Waterproofing provides a balance between material intensity and durability, confirming the trade-offs between embodied impacts and long-term maintenance requirements.

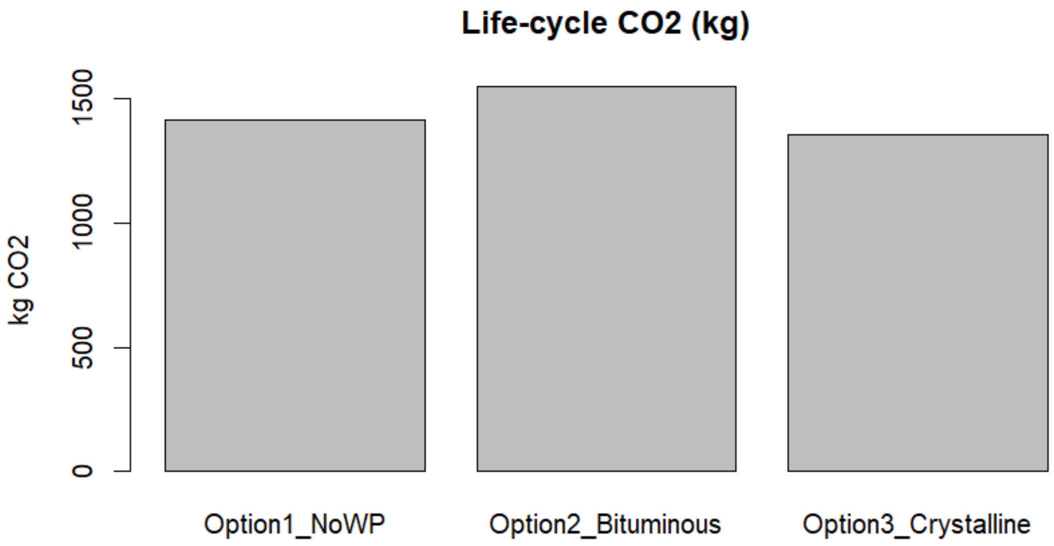


Figure 5: CO_2 (kg)

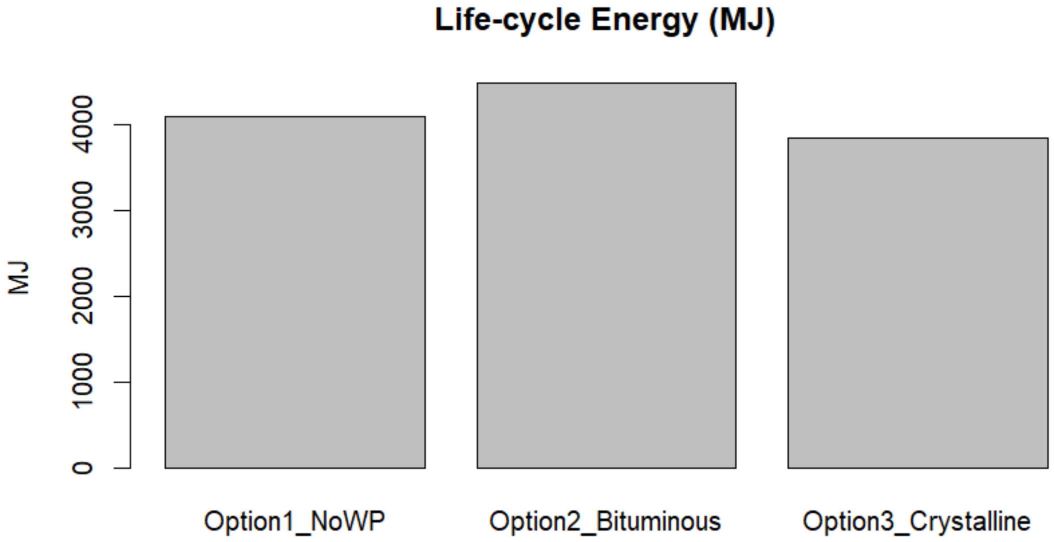


Figure 6: Energy (MJ)

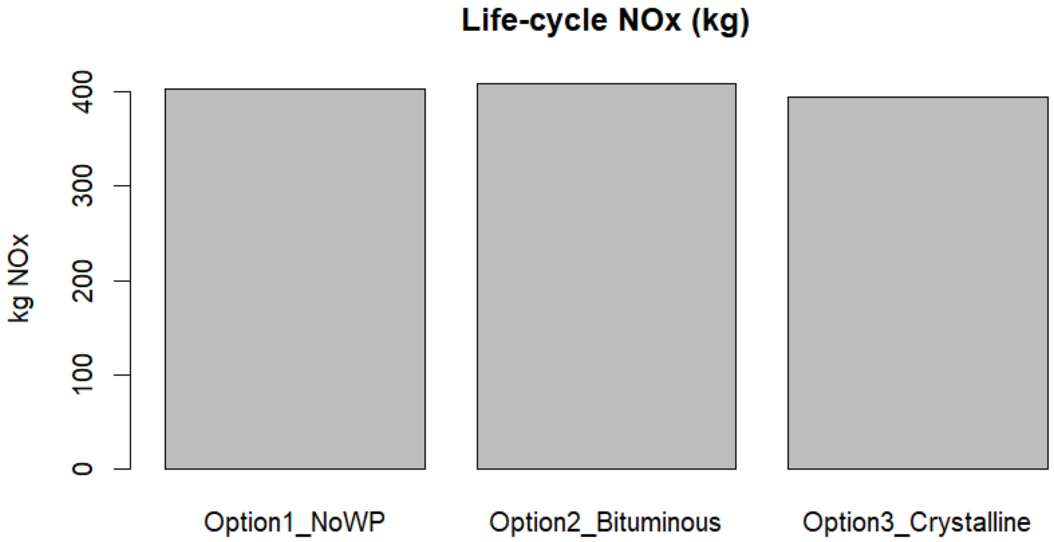


Figure 7: NOx (kg)

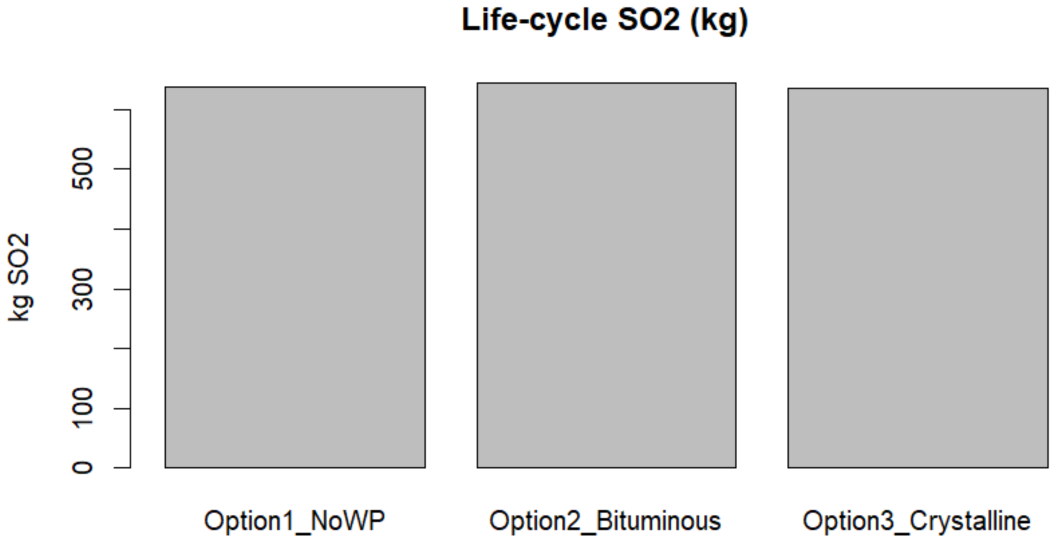


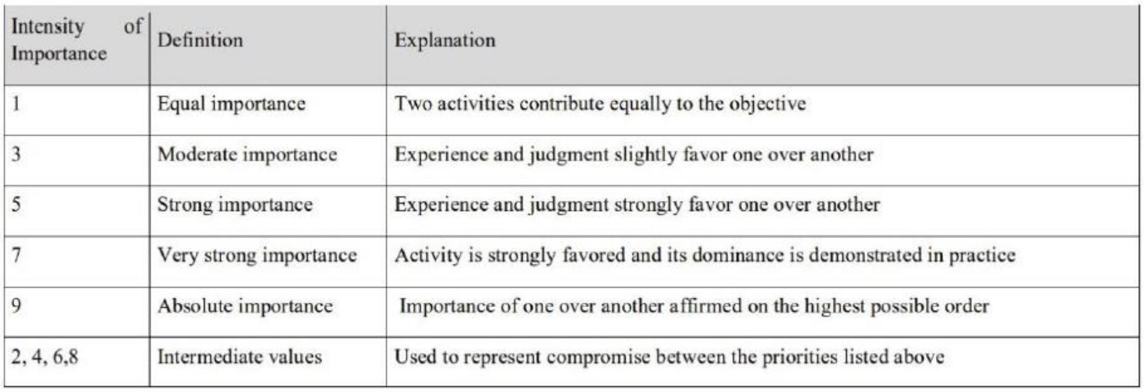
Figure 8: SO_2 (kg)

5. MCDM – Analytic hierarchy process (AHP)

5.1. Pairwise Comparisons

Table 5 presents the fundamental Saaty (1980) scale, which is the cornerstone of the Analytic Hierarchy Process (AHP) and provides a consistent numerical framework for making pairwise comparisons between alternatives. The scale ranges from 1 (equal importance) to 9 (absolute importance), with intermediate values (2, 4, 6, 8) allowed to capture more nuanced judgments. In this project, the Saaty scale was used to construct pairwise comparison matrices for the three retaining wall waterproofing alternatives—No Waterproofing, Bituminous Membrane, and Crystalline Waterproofing—based on their relative performance in the four environmental criteria: Energy, CO_2, NO_x, and SO_2. Instead of relying on subjective expert judgment, the project derived the pairwise values directly from the quantified LCA results, meaning that alternatives with lower emissions were assigned higher relative importance (i.e., more favorable) when compared to those with higher emissions. By converting the numerical performance outcomes into consistent Saaty-scale ratios, the AHP method enabled an objective aggregation of multiple environmental indicators into a single priority score. This approach ensured that the decision-making process remained transparent, reproducible, and grounded in measurable environmental data rather than subjective preference.

Table 5: (Saaty, 1980)



Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one over another
5	Strong importance	Experience and judgment strongly favor one over another
7	Very strong importance	Activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	Importance of one over another affirmed on the highest possible order
2, 4, 6,8	Intermediate values	Used to represent compromise between the priorities listed above

6. Results and discussion

The results of this study bring together the complete life-cycle evaluation of the three waterproofing strategies applied to a reinforced-concrete retaining wall stem: Option 1 – No Waterproofing, Option 2 – Bituminous Membrane, and Option 3 – Crystalline

Waterproofing. These results integrate the full material Life-Cycle Inventory (LCI), the quantified environmental impacts across four key indicators (CO_2, Energy, NOx, and SO_2), the life-cycle maintenance timeline, and the multi-criteria ranking derived using the Analytic Hierarchy Process (AHP). Together, the outputs provide a clear understanding of the environmental trade-offs and long-term sustainability performance associated with each waterproofing strategy.

The Life-Cycle Assessment (LCA) revealed substantial differences between the three alternatives. Across all four environmental indicators, the bituminous membrane exhibited the highest overall environmental burden, driven largely by the high embodied energy of bitumen production and the two major replacement cycles required at mid-life (40 years) and late-life (80 years). This is reflected most clearly in the Life-cycle Energy and Life-cycle CO_2 figures, where the bituminous option consistently shows the highest bar values. The membrane requires multiple full replacements over the 100-year lifespan, resulting in recurring emissions from transportation, material production, and installation activities. In addition, the small but frequent minor repairs (e.g., at years 30, 60, 90) add incremental material consumption that accumulates over the system lifetime. From an environmental standpoint, the bituminous system therefore performs the worst among the three alternatives.

In contrast, the Crystalline Waterproofing option demonstrates moderate environmental performance. Although crystalline coatings require chemically intensive manufacturing—reflected in their embodied CO_2 and SO_2 emissions—they are applied only once and are known for their long-term durability. This reduced need for major repair or replacement is evident in the Shiny-generated timeline figure, where crystalline waterproofing shows only one crack-repair event over the entire 100-year period, in addition to routine drainage cleaning. As a result, this option consistently performs better than the bituminous membrane in all impact categories, particularly in Energy and NOx, where it shows noticeably lower totals. However, it is not the top performer, as the initial chemical manufacturing still contributes more emissions than using no waterproofing at all. Thus, crystalline waterproofing occupies an intermediate position, balancing durability and environmental cost.

The most environmentally favorable option across all indicators is Option 1 – No Waterproofing. Even though it requires more frequent crack/spall repairs (approximately every 15 years), the associated material quantities are relatively small and the maintenance interventions involve lower-impact materials such as small repair patches or injection resins. The Life-cycle CO_2 figure clearly shows that this option produces the lowest greenhouse gas emissions, while the SO_2 and NOx figures also demonstrate a consistently low environmental footprint. Importantly, the absence of any waterproofing materials eliminates the high embodied emissions associated with bitumen or crystalline systems. Despite having more maintenance events than crystalline waterproofing, the overall environmental load remains the lowest due to the minimal material intensity of each repair action and the absence of high-emission coating materials.

The comparative analysis across all indicators confirms a coherent pattern:

- Best environmental performance: No Waterproofing
- Intermediate: Crystalline Waterproofing
- Worst environmental performance: Bituminous Membrane

These findings were further validated through the Analytic Hierarchy Process (AHP). The AHP results assign the highest overall priority weighting to No Waterproofing (≈39%), followed by Bituminous Membrane (≈34.5%), and finally Crystalline Waterproofing (≈26.3%). Although the bituminous option received a higher AHP score than crystalline waterproofing—because the AHP is sensitive to relative differences in certain indicators—its overall LCA profile still shows it as the most emission-intensive option. The consistency between the LCA impacts and the AHP priority values reinforces the conclusion that No Waterproofing is the most environmentally sustainable alternative, and that bituminous systems impose the highest life-cycle burden.

In engineering terms, these results are meaningful because they highlight the trade-off between embodied impacts and long-term durability performance. Bituminous membranes, while effective as a barrier system, come with a substantial environmental cost due to their petrochemical nature and replacement frequency. Crystalline waterproofing adds durability benefits but still relies on energy-intensive chemical production. Meanwhile, opting for exposed reinforced concrete with no added waterproofing performs best environmentally, provided that the structural detailing (proper cover, drainage provision, and maintenance accessibility) is adequate to control moisture ingress over time.

Overall, the combination of LCI, LCA, maintenance timeline modeling, and AHP presents a holistic evaluation framework that shows how engineering decisions in waterproofing can have major long-term environmental implications. The results demonstrate that even a single design choice—such as whether to apply an external membrane—can lead to measurable differences in CO_2 emissions, energy use, and pollutant outputs over a century-long service life. For engineering practice, this highlights the importance of integrating sustainability metrics into routine design decisions and reinforces that low-intensity solutions, when feasible, can significantly reduce the carbon footprint of everyday infrastructure elements.

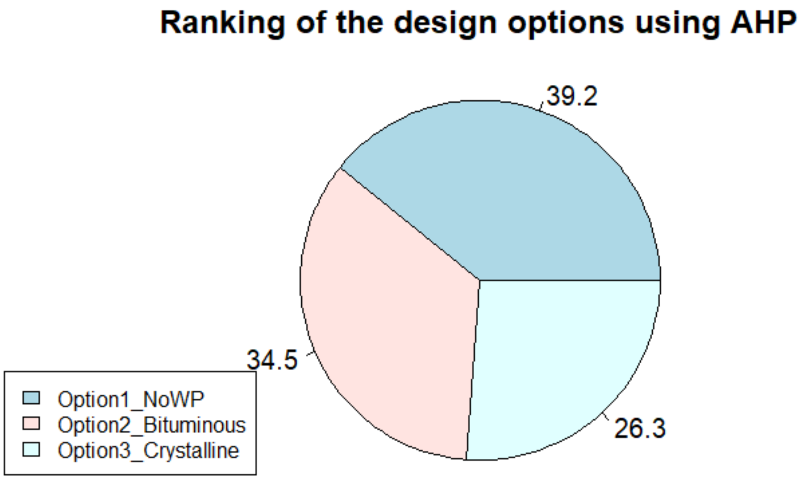


Figure 9: AHP-Derived Priority Weights for the Three Waterproofing Design Options

7. Conclusion

1. Carbon footprint analysis should be integrated into routine design, not treated as an afterthought.
2. Even a simple subsystem (one retaining wall stem) reveals large differences in environmental performance.
3. Engineers can use results like these to:
    - Optimize waterproofing strategies based on environmental performance
    - Improve concrete mix design (e.g., use SCMs)
    - Minimize unnecessary membrane replacements
    - Select coatings or membranes with lower embodied emissions

    - Communicate transparently with clients and regulators

4. LCA + AHP provides a repeatable, transparent framework for comparing alternatives.
5. Future work can incorporate:
    - Cost
    - Durability modeling
    - Risk of failure
    - End-of-life recycling

Overall, the analysis confirms that No Waterproofing is environmentally preferred for moderate exposure conditions, while Bitumen and Crystalline systems impose higher long-term impacts. These insights allow engineers to design more sustainable infrastructure with informed decision-making.

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