Life-Cycle Assessment & Multi-Criteria Decision Making

An RCC Slab Example

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Introduction

Environmental sustainability has become a critical focus across industries, including construction, due to its significant contribution to global energy consumption and greenhouse gas emissions. The construction industry alone accounts for over 40% of global energy demand and produces approximately 33% of annual CO_2 emissions[1]. These figures emphasize the urgency of minimizing environmental impacts during various stages of construction.

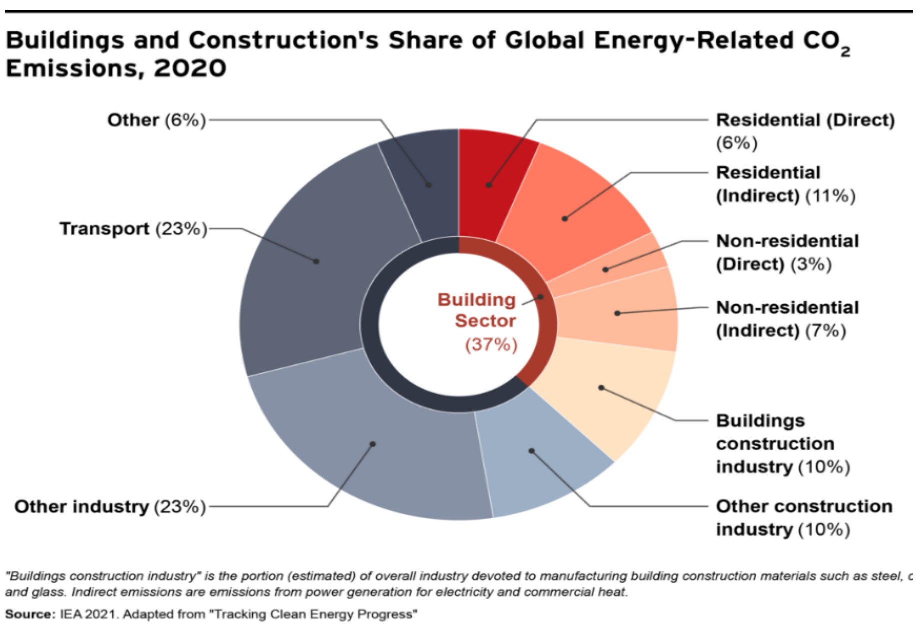

Figure 1. Building and Construction's share of Global Energy- CO_2 Emission[1]

Although the construction phase, which consists of several phases, is relatively shorter than the operation and maintenance phase, its environmental impact should be considered, since large amounts of building materials are used to construct a building in this stage[2]. Studies suggest that

[1] International Energy Agency. "Global CO_2 Emissions from Buildings (2022)." *IEA*, 2022, https://www.iea.org/data-and-statistics/charts/global-co2-emissions-from-buildings-including-embodied-emissions-from-new-construction-2022

[2] Paik, I.; Na, S. Comparison of Environmental Impact of Three Different Slab Systems for Life Cycle Assessment of a Commercial Building in South Korea. *Appl. Sci.* **2020**, *10*, 7278. https://www.mdpi.com/2076-3417/10/20/7278.

optimizing building materials, such as by using low-carbon alternatives or high-strength materials, can reduce environmental burdens by up to 50% [3].

1. Goal and Scope Definition

The goal of this study is to evaluate the environmental impacts of three different reinforced concrete slab systems-Ordinary Solid Slab (OSS), Flat Plate Slab (FPS), and Voided Slab System (VDS), within the context of a university building in Pokhara, Nepal. Slabs are critical structural elements that ensure load transfer to supporting beams and columns while providing flat, functional surfaces for building occupants.

With urban development expanding globally, including in Nepal, university campuses often incorporate multi-story buildings that demand efficient slab systems. Traditional slab construction methods, like the OSS, involve significant quantities of concrete and steel reinforcement, which increase self-weight, construction costs, and time. In contrast, alternative systems such as FPS and VDS reduce material usage, construction time, and costs, making them viable solutions for sustainable development. This study focuses on assessing these slab systems during the construction phase to identify their environmental impacts and relative advantages.

1.1 System Boundary

In this study, the system boundary for assessing the environmental impact of the three slab systems-Ordinary Solid Slabs (OSS), Flat Plate Slabs (FPS), and Voided Deck Slabs (VDS)-is confined to the construction phase (i.e., cradle to pre-operation). The assessment includes:

I. Material Production: Emissions and energy consumption from raw material extraction and processing (e.g., cement, steel reinforcement, and aggregates).
II. Construction Phase: Emissions from material transportation to the construction site and on-site construction activities involving machinery and equipment.

The assessment excludes other building components (e.g., walls, beams, non-structural elements), operational energy use, and deconstruction and disposal processes at the end of life. Unlike previous studies focusing on environmental indicators such as GWP, AP, EP, ODP, POCP, and ADP, this study evaluates environmental impacts through **energy consumption and emissions of pollutants, including Carbon Dioxide (CO2), Sulfur Dioxide (SO2), and Nitrogen Oxides (NOx)**.

[3] Goverse, Tessa, et al. "Wood innovation in the residential construction sector; opportunities and constraints." *Resources, conservation and recycling* 34.1 (2001): 53-74. https://www.sciencedirect.com/science/article/pii/S0921344901000933.

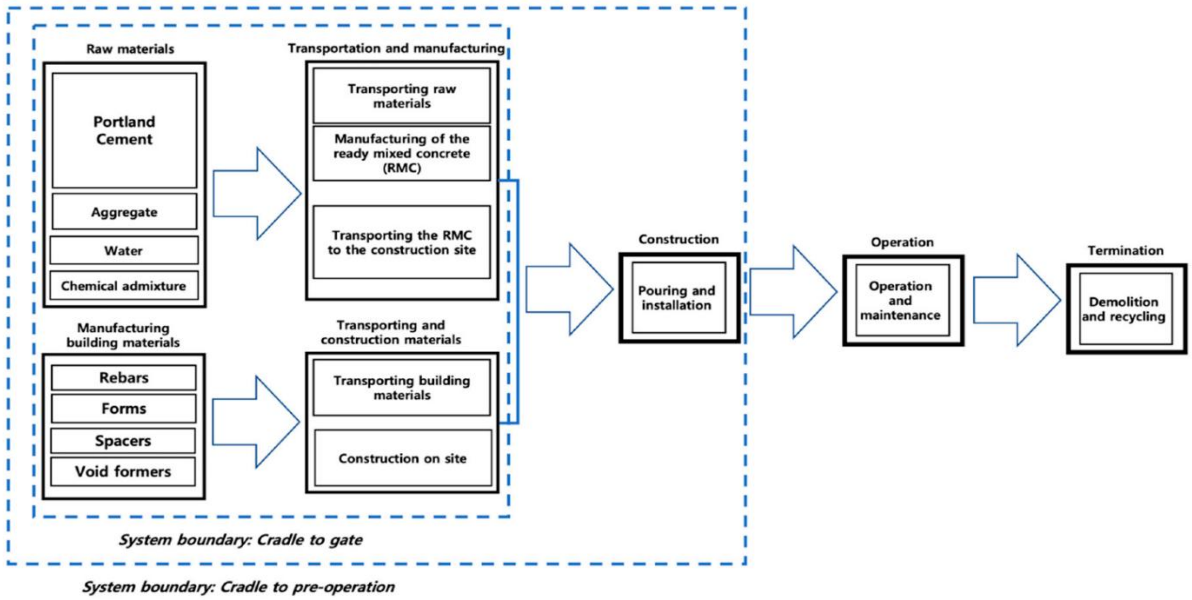

Figure 3: System Boundary for the construction process[4]

1.2 Design Options and Parameterization

Table 1. Design Options with Parameters and Scope

Design Options	Slab Type	Cross-Section	Depth(m)	Scope
1	OSS (Ordinary Solid Slab)	L = 5 m, B = 5 m	0.25	Conventional, uses more concrete.
2	FPS (Flat Plate Slab)	L = 5 m, B = 5 m	0.20	Requires the highest reinforcement.
3	VDS (Voided Deck Slab)	L = 5 m, B = 5 m	0.15	Lightweight, uses voided materials.

Based on the literature **Paik et. al.**, the slab types can be described as:

Option 1 (OSS – Ordinary Solid Slab):

OSS uses the most concrete among the three design options. These slabs have a significant depth, which provides some inherent resistance to bending. This slab type is straightforward and widely used for conventional construction.

[4] Paik, I.; Na, S. Evaluation of Carbon Dioxide Emissions amongst Alternative Slab Systems during the Construction Phase in a Building Project. *Appl. Sci.* **2019**, *9*, 4333. https://www.mdpi.com/2076-3417/9/20/4333.

Option 2 (FPS – Flat Plate Slab):
These slabs are significantly thinner than solid slabs, relying heavily on two-way spanning and reinforcement to resist bending and shear stresses. This often translates to higher reinforcement requirements compared to the other two types.

Option 3 (VDS – Voided Deck Slab):
VDS (also called Bubble Deck Slab) uses void fillers like recycled plastic spheres to replace concrete in non-structural zones. The concrete volume is significantly reduced. It has minimum depth making it a lightweight and innovative solution for reducing material usage.

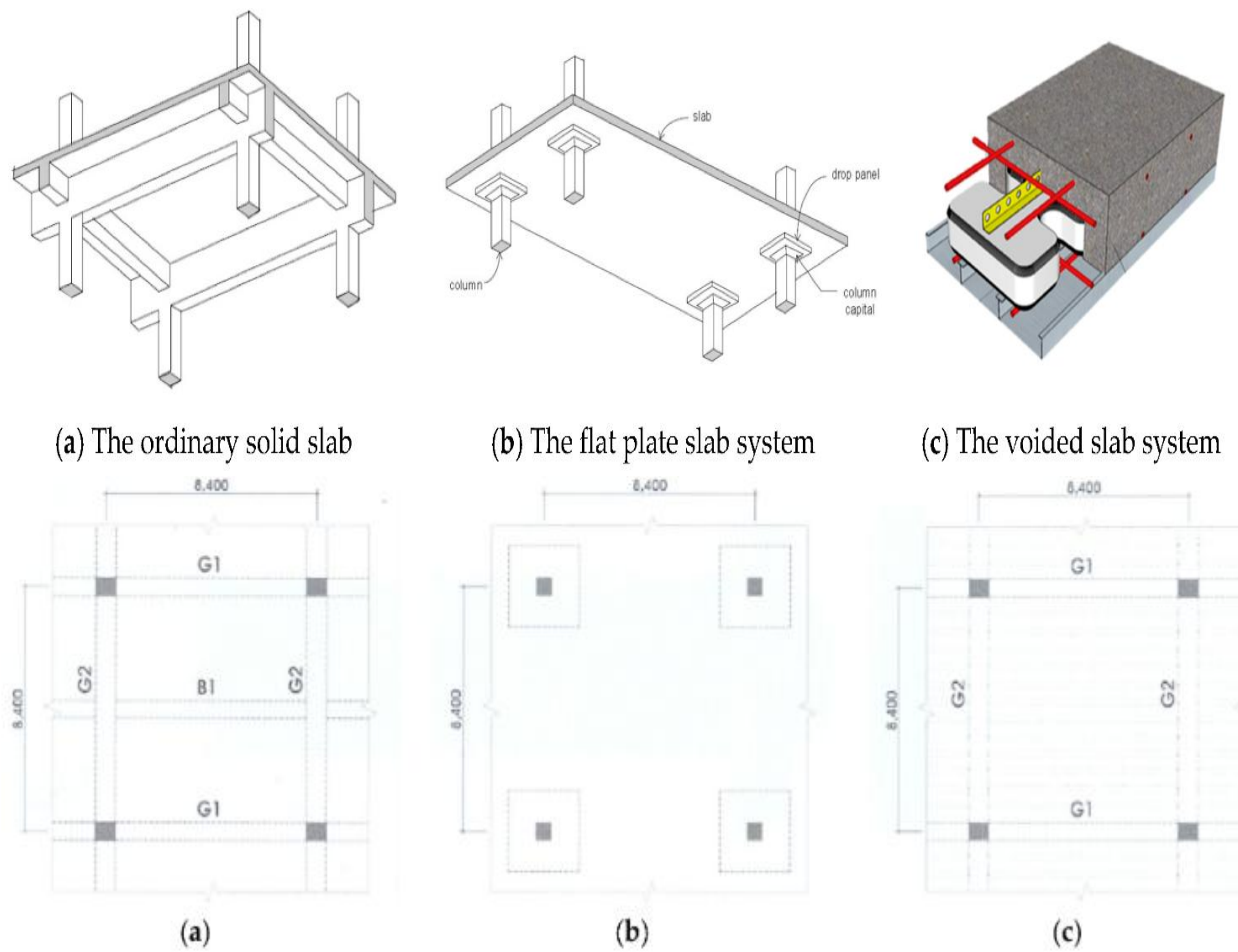

Fig 4: Schematics of the Slab System in a Building[6]

1.3 Description of the Case Study

The slabs of the studied university building were designed using three reinforced concrete slab systems: OSS, FPS, and VDS.

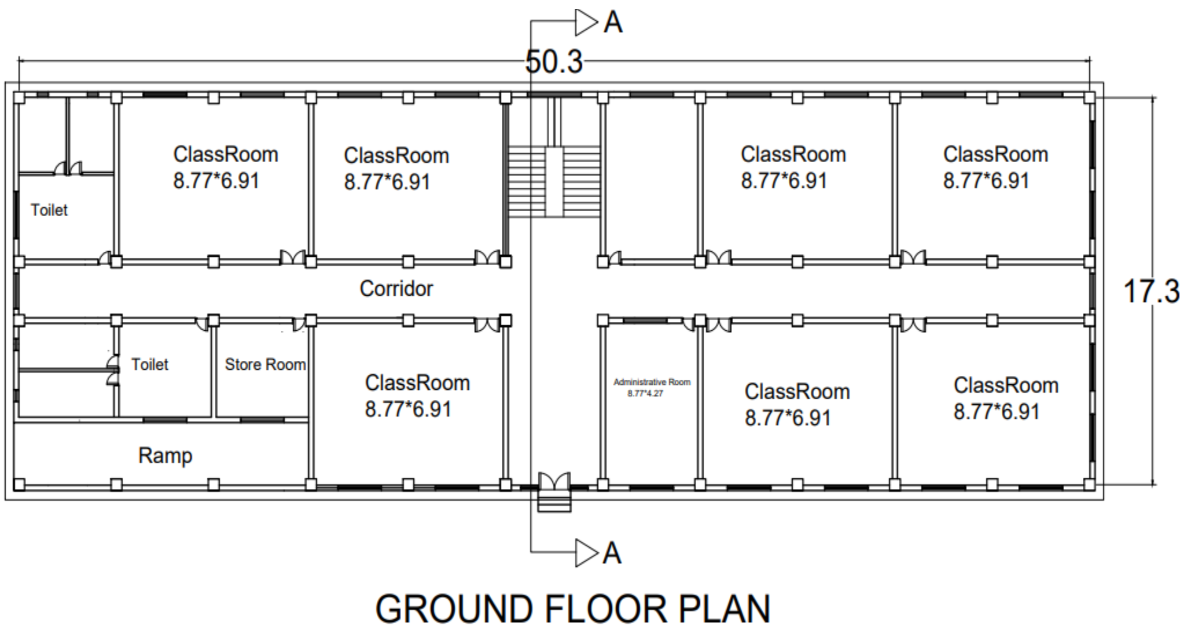

Fig 5: Ground Floor Plan of the Proposed Building

Profile of the Studied Building:

- Building Type: University building with lecture halls and administrative offices.
- Structure: Rigid-frame structure with reinforced concrete slabs.
- Size: The typical floor area is approximately 850 m², and the total building floor area is 2,550 m² (five stories).
- Construction Period: The proposed design assumes a construction timeline of two years.

The slab thicknesses were 200 mm for OSS, 250 mm for FPS, and 150 mm for VDS. Reinforcement consisted of 12 mm and 16 mm diameter deformed bars with a yield strength of 415 MPa, suitable for Nepal's seismic requirements. The 12 mm rebars were used for upper reinforcement, while 16 mm rebars were placed for lower layers.
These slab systems are adaptable for educational buildings, balancing architectural layout and cost-efficiency. FPS and VDS were suggested as alternatives to OSS during the design phase for their material efficiency and faster construction timelines.

2. Life-Cycle Timeline

For the lifecycle timeline interventions, the events (Maintenance, Repair, Replacement, and Partial Replacement) and their frequencies are based on standard practices and adapted from literature on slab maintenance, such as Jung et al. (2008)[5].

I. Maintenance (M): OSS and FPS designs require less frequent maintenance due to their durability. VDS, being more vulnerable to wear, requires maintenance every 7 years.
II. Repair (R): FPS, being relatively durable, has a longer repair cycle (15 years). OSS and VDS require more frequent repairs (12 and 10 years, respectively).
III. Replacement/Partial Replacement (RP/PR): Adjusted to match typical slab lifespans. For VDS, partial replacements occur at 20 years due to its quicker degradation.

Table 2: Interventions and their Frequencies for different Design Options

Design Option	Event	Frequency	Total Lifespan
1.Ordinary Solid Slab	M	8	50
1.Ordinary Solid Slab	R	12	50
1.Ordinary Solid Slab	RP	30	50
2.Flat Plate Slab	M	10	50
2.Flat Plate Slab	R	15	50
2.Flat Plate Slab	RP	35	50
3.Voided Deck Slab	M	7	50
3.Voided Deck Slab	R	10	50
3.Voided Deck Slab	PR	20	50

Where, M = Maintenance, R = Repair, RP = Replacement, PR = Partial Replacement
Now, the interventions related data of slab design is uploaded in a web application framework for R called **Shiny**. Then, the interventions are displayed on the following timelines:

[5] Jung, Youn su, et al. *Evaluation and Selection Guide of Method of Repair for Routine Maintenance*. Texas Transportation Institute, Apr. 2008. https://rosap.ntl.bts.gov/view/dot/16856.

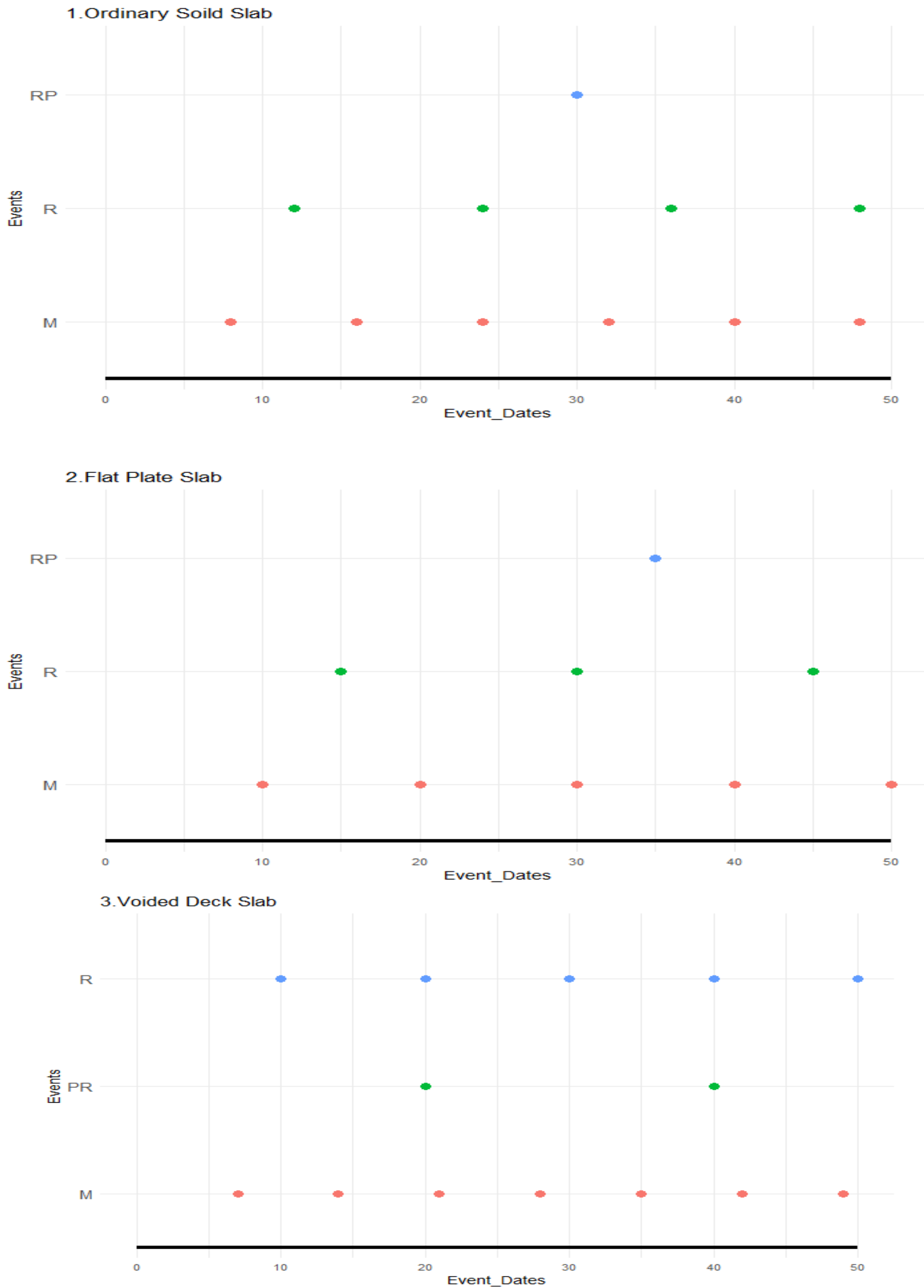

Fig 6: Interventions Timeline for OSS, FPS and VDS

The figures show time spans for different slab design options so that the asset managers can plan different interventions effectively on time. By following the timeline strictly, we can ensure minimal disruption, cost optimization, and long-term performance.

3. Life-Cycle Inventory Analysis

Table 3: Lifecycle Inventory Materials for RCC Slab Construction

Material	Scope	Quantities(kg/m^3)	Energy (MJ/t)	CO2 (kg)	NOX (kg)	SO2 (kg)
Cement	OSS	382.4	3.26	0.822	0.177	0.065
Coarse Aggregate	OSS	1057	0.0035	0.016	0.0018	0.0018
Fine Aggregate	OSS	837	0.0023	0.0053	0.009	0.009
Reinforcement Steel	OSS	305	2430	225	0.71	1.85
Forms	OSS	50	0.5	0.02	0.01	0.005
Cement	FPS	234.8	3.26	0.822	0.177	0.065
Coarse Aggregate	FPS	946	0.0035	0.016	0.0018	0.0018
Fine Aggregate	FPS	555	0.0023	0.0053	0.0009	0.0009
Reinforcement Steel	FPS	350	2430	225	0.71	1.85
Forms	FPS	50	0.5	0.02	0.01	0.005
Cement	VDS	187.7	3.26	0.822	0.177	0.065
Coarse Aggregate	VDS	805	0.0035	0.016	0.0018	0.0018
Fine Aggregate	VDS	512	0.0023	0.0053	0.009	0.009
Reinforcement Steel	VDS	215	2430	225	0.71	1.85
Forms	VDS	50	0.5	0.02	0.01	0.005
Steel Decking	VDS	40	2430	225	0.71	1.85
Void Fillers	VDS	128	169.69	3.09	0.766	0.036

The scope column indicates the use of a specific material in the composition of a specific RCC slab type like OSS = Ordinary Solid Slab, FPS = Flat Plate Slab, VDS = Voided Deck Slab

Clarification: Cement production significantly impacts CO_2 emissions in RCC slabs. Aggregates have low energy use and emissions due to simpler processing. Reinforcement steel, with high energy needs, adds to environmental impact. VDS uses steel decking and void fillers, which emit moderately but reduce concrete usage. SO_2 and NOx emissions mainly come from transport and equipment. Emission and energy consumption values were adapted from reliable datasets, including the National Life Cycle Inventory Database and Ökobaudat[6] to ensure consistency with industry standards. These values were then adjusted according to the regional context of Pokhara, Nepal, considering local construction practices and material availability.

[6] Federal Ministry of the Interior, Building and Community. *Ökobaudat: Life Cycle Inventory Database for Building Materials*. Germany, 2021.

4. Life-Cycle Cost Analysis

Assumptions:

- All slab systems are designed for the same structural load capacity with lifespan of 50 years.
- Costs are calculated per square meter of slab area and are based on Nepal's market data (2024), subject to inflation and market variations. The costs (NPR) are taken in in equivalent to Euros for better understanding.
- Maintenance frequency and repair intervals are derived from statistical data and industry standards.

Table 4: Estimated Life-Cycle Costs

Cost Component (€)	**OSS**	**FPS**	**VDS**
Materials	450	520	600
Construction	100	130	160
Maintenance (50 years)	300	250	450
Total LCC	**850**	**900**	**1,210**

OSS is the cheapest option due to low material and maintenance costs while VDS is the most expensive because of costly materials, complex production, and higher maintenance needs.

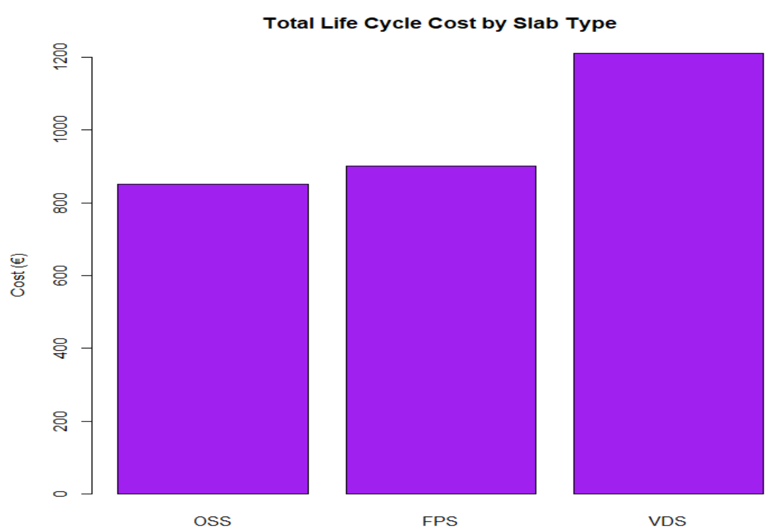

Fig7: Visualization of total life-cycle costs of different slab types obtained from R

5. Results and Discussions

5.1. Total Energy Consumption and Emissions of Each Slab System

The life-cycle assessment (calculation of energy consumption and emissions) for each of the slab systems is carried out in RStudio. The formula for calculating the environmental impacts of each design option is structured in R-script as shown below.

```
# Calculate LCA metrics for each material
LCA.matrix <- mutate(slab.materials,
                     TotalMaterials.Q = quantities * slab.Q / 1000,  # Convert quantities to tons
                     materials.LC = TotalMaterials.Q,
                     Energy.LC = materials.LC * energy,             # Energy consumption
                     CO2.LC = materials.LC * CO2 * 1000,            # CO2 emissions
                     NOx.LC = materials.LC * NOX * 1000,            # NOx emissions
                     SO2.LC = materials.LC * SO2 * 1000)            # SO2 emissions

# Summarize results
LCA.results <- list(Energy = sum(LCA.matrix$Energy.LC),
                    CO2 = sum(LCA.matrix$CO2.LC),
                    NOx = sum(LCA.matrix$NOx.LC),
                    SO2 = sum(LCA.matrix$SO2.LC))
```

Then the slab design parameters for each option based on our case study is assigned to the R-script and following LCA result is produced in the console.

```
> print(results)
      Energy      CO2       NOx      SO2
OSS 4640.170 431010.5 1838.5650 3742.448
FPS 3405.180 315848.3 1171.0476 2660.857
VDS 1444.525 130368.2  717.4753 1113.447
```

Talking about the units of LCA results, Energy consumption is calculated in MJ, and all the emissions (CO2, NOX and SO2) are calculated in kilograms(kg).
For better visualization and comparative analysis, the results are interpreted on bar plots for each of the environmental impact indicators in R which are presented below.

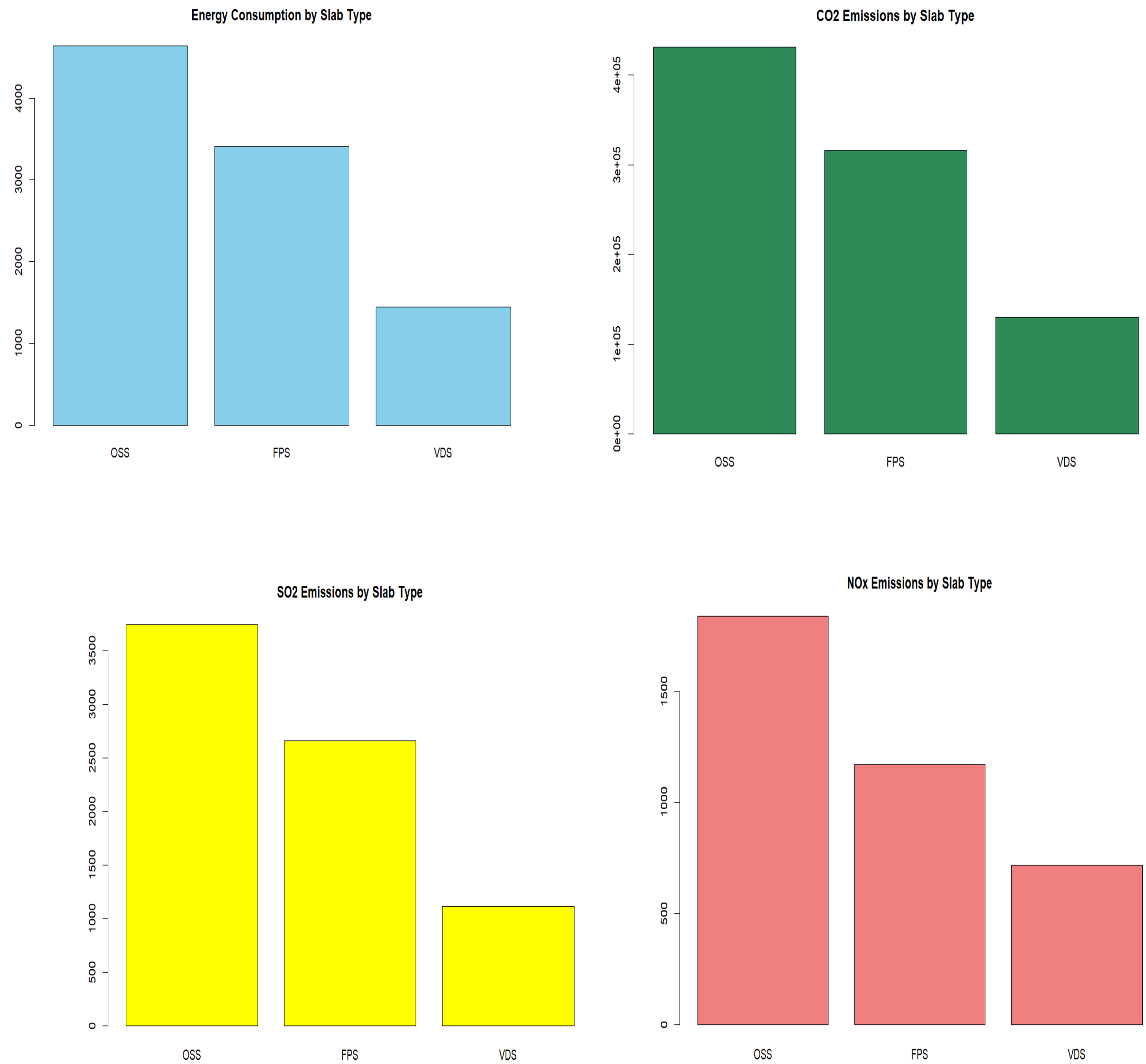

Fig 7: Bar plots showing the Energy Consumption and Emissions for different Slab Options

I. Total Energy Consumption by Slab Type

OSS exhibits the highest energy consumption (4640.170 MJ), followed by FPS (3405.180MJ), and VDS (1444.525 MJ). The significantly higher energy consumption in OSS can be attributed to its material-intensive nature. Specifically, FPS, though using more materials, consumes less energy than OSS due to its efficient design. VDS, as the lightest option, uses the least materials and has the lowest energy consumption. This comparative analysis shows the impact of material choice and design optimization on the energy footprint of slab systems.

II. Emissions by Slab Type

Ordinary Solid Slab has the highest emissions of CO2 (4.31×10^5 kg), SO2 (3742.448 kg), and NOx (1838.565 kg). This is because it uses more cement and steel. Cement is carbon-intensive, producing large amounts of CO2 during production. Steel adds more emissions due to its energy-intensive manufacturing process. FPS emits less compared to OSS. It uses materials efficiently. Still, its cement and steel use contribute to moderate SO2 and NOx emissions. VDS has the lowest emissions. Its lightweight design uses less concrete and steel. Fewer materials mean fewer emission.

5.2. Multi-Criteria Decision-Making Analysis-Analytic Hierarchic Process (AHP)

The Analytic Hierarchy Process (AHP) was employed to rank three slab design options: OSS, FPS, and VDS, based on four criteria: energy consumption, CO2, NOx, and SO2 emissions. This structured decision-making approach ensures consistency in pairwise comparisons, following Saaty's 1–9 scale, which represents the relative importance of elements (1: equal importance, 9: extreme importance).

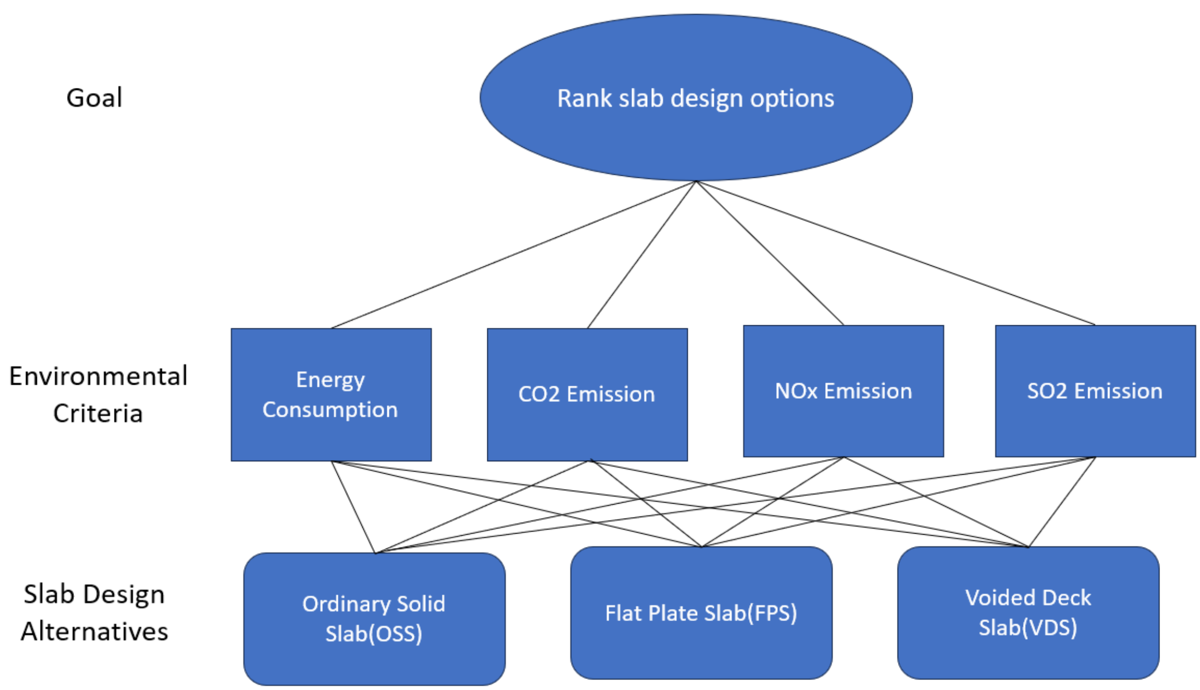

Fig 8: Generic Hierarchic Structure

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Table 5: Saaty's 1-9 Intensity of Importance Table[7]

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective.
3	Moderate Importance of One Over Another	Experience and judgment slightly favor one activity over another.
5	Strong Importance of One Over Another	Experience and judgment strongly favor one activity over another.
7	Very Strong Importance	An activity is strongly favored, and its dominance is demonstrated in practice.
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate Values	Used to represent compromises between the preferences in adjacent judgments.

Pairwise comparison matrices are developed for each criterion (energy, CO2, NOx, SO2) and for the criteria themselves. Each matrix is tested for reciprocity (e.g., $a_{ij} = 1/a_{ji}$) to ensure consistency.

```
# Step 3: Define Pairwise Comparison Matrices for Alternatives
# Energy comparison matrix
energy <- matrix(c(
  1, 1/3, 2,
  3, 1, 5,
  1/2, 1/5, 1
), nrow = 3, byrow = TRUE, dimnames = list(alternatives, alternatives))

#Test the reciprocal condition
energy == t(1/energy)

# CO2 comparison matrix
CO2 <- matrix(c(
  1, 1/2, 4,
  2, 1, 6,
  1/4, 1/6, 1
), nrow = 3, byrow = TRUE, dimnames = list(alternatives, alternatives))
```

```
# NOx comparison matrix
NOx <- matrix(c(
  1, 2, 3,
  1/2, 1, 4,
  1/3, 1/4, 1
), nrow = 3, byrow = TRUE, dimnames = list(alternatives, alternatives)

# SO2 comparison matrix
SO2 <- matrix(c(
  1, 3, 5,
  1/3, 1, 2,
  1/5, 1/2, 1
), nrow = 3, byrow = TRUE, dimnames = list(alternatives, alternatives)
```

Fig 9: Pairwise Comparison Matrices for each criterion from R

Justification on assumptions for pairwise comparison matrices:

The energy comparison matrix evaluates energy use among OSS, FPS, and VDS. OSS is moderately less efficient than FPS due to FPS's optimized material usage, so rated 1/3. OSS is strongly preferred

[7] Saaty, Thomas L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. McGraw-Hill International, 1980. https://archive.org/details/analytichierarch0000saat.

over VDS, which uses minimal materials, rated 2. FPS is strongly preferred over VDS for better efficiency, rated 5. The criteria in AHP are weighted based on their perceived importance as per industry standards and sustainable construction practices.

For CO2 emissions as an example, OSS emits more due to high cement and steel use, rated 1/2 compared to FPS. OSS is strongly preferred over VDS, rated 4, as VDS uses void fillers and less concrete. FPS emits more than VDS due to reinforcement needs, rated 6.

Similarly, pairwise comparison matrix is formulated for criteria in R:

```
# Step 4: Define Pairwise Comparison Matrix for Criteria
CWPC <- matrix(c(
  1, 2, 3, 4,
  1/2, 1, 2, 3,
  1/3, 1/2, 1, 2,
  1/4, 1/3, 1/2, 1
), nrow = 4, byrow = TRUE, dimnames = list(indicators, indicators))
```

The ratings follow the Greenhouse Gas Protocol, prioritizing energy for its direct environmental impact, followed by CO2 for its contribution to global warming. NOx is rated next for its role in acidification, with SO2 rated lowest due to its relatively smaller impact.

Visualization and Interpretation:

The final rankings are visualized through a pie chart. FPS emerged as the top-ranked design (54.5%), followed by OSS (34.2%) and VDS (11.3%). The high rank of FPS reflects its balanced performance across all criteria, particularly in CO2 emissions and energy efficiency.

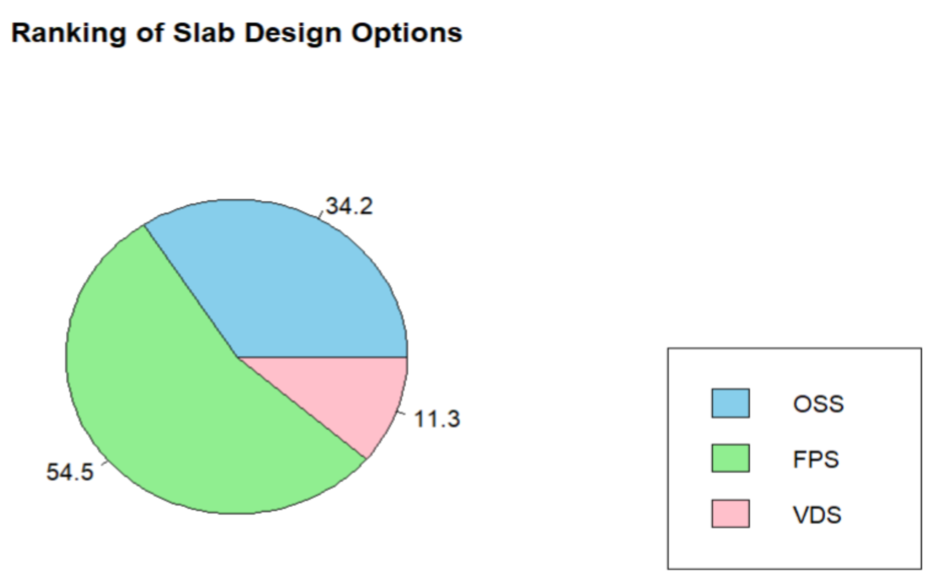

Fig 10: Ranking of the slab design options using AHP

5.3. Discussion

In this project, two key narratives emerge from the analysis of slab design options: the environmental impact assessment and the results of the Analytic Hierarchy Process (AHP). The environmental impact assessment, calculated using RStudio, indicates that the Voided Deck Slab (VDS) has the lowest energy consumption and emissions, making it the most environmentally friendly option

among all design options. OSS exhibits the highest energy consumption and emissions, primarily due to its heavy material use and greater thickness, while FPS ranks in between the two.
However, the AHP analysis provides a contrasting perspective. By integrating multiple criteria and weighting their relative importance, FPS emerges as the top-ranked option with a 54.5% preference. This divergence is showing the importance of considering a broader set of criteria beyond just environmental impacts.

- Key Reflections and Justifications:

Material Availability and Familiarity: As this assessment is based on a specific case study in Nepal, FPS benefits from the availability of materials and the familiarity of local construction professionals. Although VDS is environmentally superior, its adoption is limited due to the lack of local expertise and the novel nature of its construction technique.
Structural Efficiency: FPS provides a balanced approach, optimizing both material use and structural performance, making it a more practical choice in scenarios where environmental impact is not the sole consideration.
Trade-Off Analysis: AHP facilitates a trade-off analysis, acknowledging that while VDS excels in reducing environmental impact, FPS offers a more balanced performance across all criteria, including structural stability and **lifecycle costs** as compared to VDS.

6. Conclusion

The assessment reflects the complexity of decision-making in sustainable construction. When it comes to the **lowest environmental impact**, Voided Deck Slab is the preferred design option. But, on the other hand, Flat Plate Slab is identified as the best overall option through AHP while focusing on practical aspects like **material availability, lifecycle costs and construction feasibility**. One more advantage in choosing FPS is its superior compliance with the Nepal Building Code (NBC 105:2020) as compared to VDS. This dual narrative demonstrates the necessity of a holistic approach in evaluating sustainable design options, where environmental benefits must be weighed against practical constraints and broader project goals.
While this study was carried out on the evaluation and comparison of the carbon dioxide emissions from an actually designed building in Pokhara, Nepal, there is a **limitation** that should be addressed in future research. In order to verify the practicability and expand the applicability of the Flat Plate Slab and Voided Deck Slab systems in building projects, more cases need to be investigated in future studies. The limitations identified, such as the current market viability and construction expertise for VDS, suggest areas for future research to enhance practical applicability. By addressing these gaps, future studies can refine the adoption of VDS, potentially making it the preferred design option. Moreover, life cycle assessment of the flat plate slab and voided slab systems during the operation and maintenance phases should be performed from the whole life cycle perspective of a building. Talking about the engineering applications of this study, the life-cycle interventions, cost analysis and environmental impact data can inform policy-makers, construction managers, and environmental agencies, aiding in strategic planning and sustainable construction practices.

References

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