Technische Universität Berlin

Civil Systems Engineering

Whole Life Civil Systems Analysis

Individual Project Assignment 2

Life-Cycle Analysis and Multi-Criteria Decision Making of a ***Precast Concrete Building****'s subsystem*

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The construction sector is one of the largest contributors to global resource consumption, energy use, and environmental emissions. As the demand for more efficient and sustainable building systems grows, engineers increasingly rely on quantitative assessment methods to evaluate the environmental performance of structural solutions. Life Cycle Assessment (LCA) provides a systematic framework for measuring the environmental impacts associated with construction materials and processes, enabling engineers to compare design alternatives on the basis of objective indicators such as Global Warming Potential (GWP) and Water Deprivation Potential (WDP).

Precast technology has been shown to offer several environmental benefits—including reduced material waste, improved quality control, and lower site impacts—due to its factory-controlled production environment and optimized material usage [1]. In this report, an LCA is carried out for three design options for a precast concrete subsystem consisting of floor slab and the supporting beams, using life cycle inventory data, with the goal of identifying the design with the best environmental performance. Then, a Multi-Criteria Decision-Making (MCDM) analysis using the Analytic Hierarchy Process (AHP) is performed to deepen the comparison between the design alternatives.

I. System Description

The subsystem chosen for this assessment is a Precast concrete floor, including both the precast floor slab and the supporting beams. Precast concrete controlled manufacturing conditions create easier tracking of the quantities and quality of the resulting component, insuring consistency for all resulting products, and making its environmental impact much easier to track.

The assessed alternatives for this subsystem will depend on the type of floor slab and concrete beam used, ranging between solid concrete slab and hollow concrete slab, and regular reinforced concrete beam and prestressed concrete beam. A sketch of the selected system is shown in *Figure 1* describing the two components that will create the variety of design options.

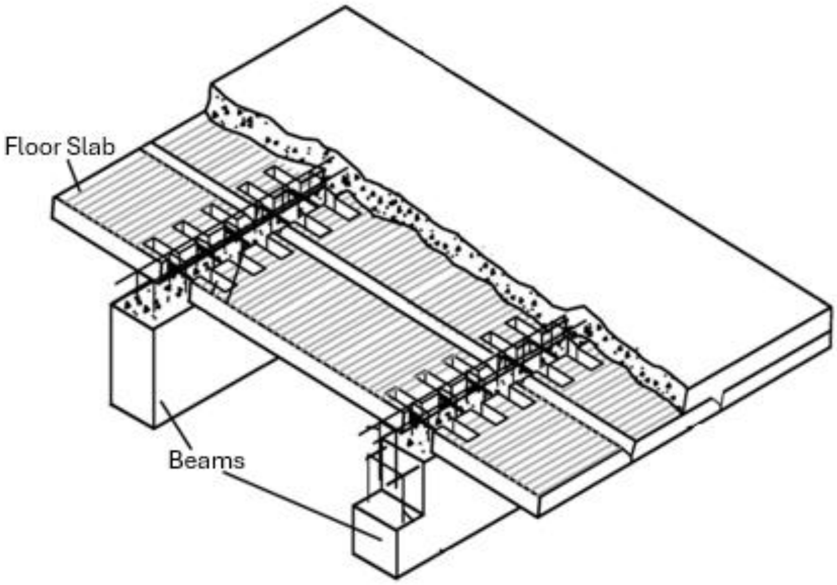


Figure 1: Selected Subsystem Sketch [1]

This Floor system is defined to have the following properties, according to which the required beam depth and floor slab thickness will be determined to create the final design quantities in order to analyze each option's environmental impact:

- Beam Span = 6 m
- Beam width = 0.25 m
- Floor panel length = 3 m
- Floor panel width = 1 m
- Concrete density = 2.5 ton/m^3

Figure 2 shows sketches for each design option.

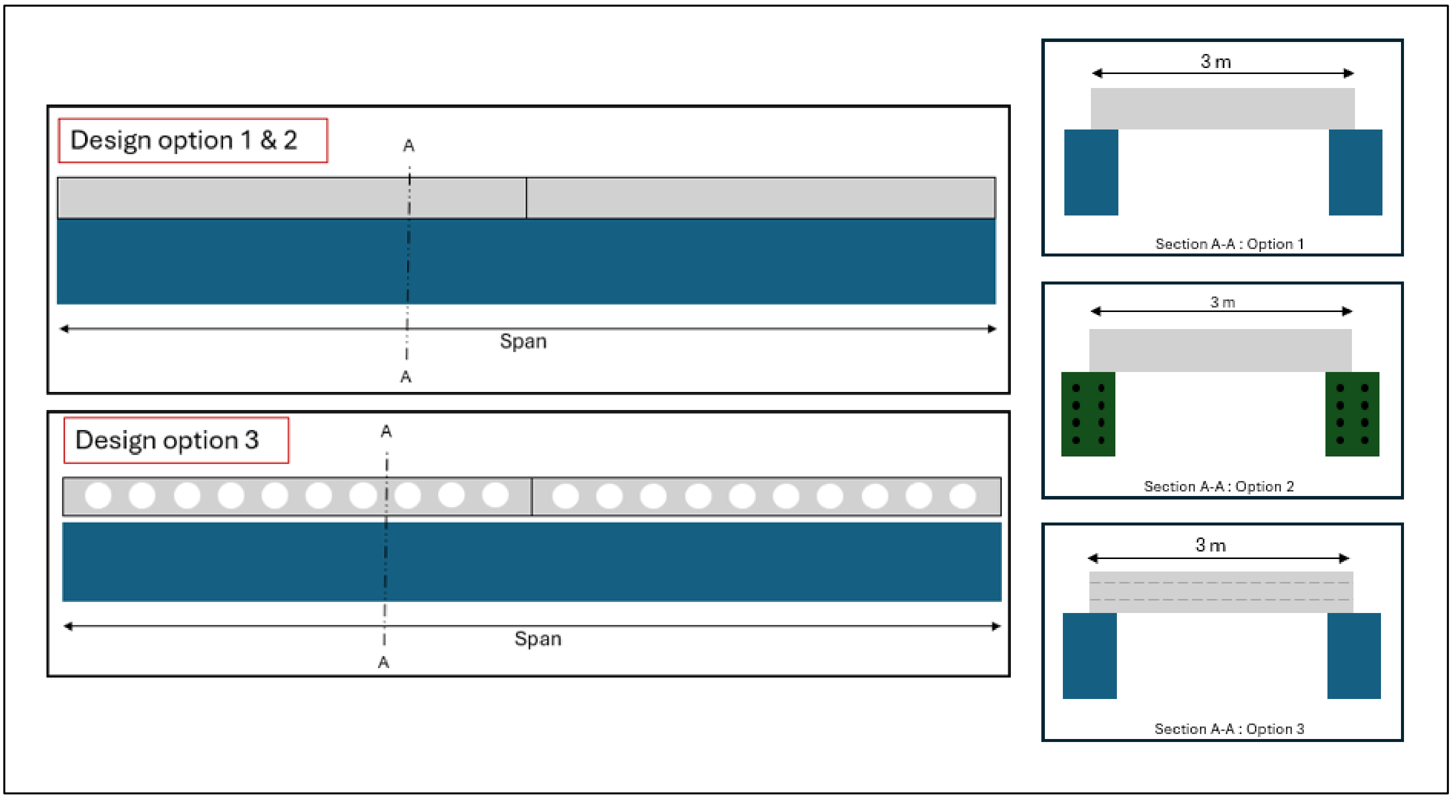


Figure 2: Design Options Sketches

II. Defining Goal and Scope

Klöpffer et al. [2] guides the process and importance of goal and scope definition. Goal of the study explains the intended application of reason for the LCA study, which in this case study is to calculate the environmental impact for each design option and evaluate the results to choose the best one. It is defined in detail through specifying the following details:

- Range of application: Evaluate and compare environmental performance of three alternative precast concrete structural floor systems
- Interest of realisation: Provide quantitative understanding of the environmental effects of different precast solutions
- Target group: Structural Engineers, clients and decision makers

Scope, on the other hand, establishes the details of this study, specifying different system stages that will be considered, impact assessment and functional unit. This study will assess the environmental performance for the three alternatives in the following stages of the components lives:

Raw material supply → transport → manufacturing → Deconstruction/ demolition → transport → waste processing → disposal → RRR potential

This assessment will be done based on the total **Global Warming Potential (GWP)** and **Water Deprivation Potential (WDP)** resulted from all above stages in the lifetime of each component. *Figure 2* describes the goal and scope of this study.

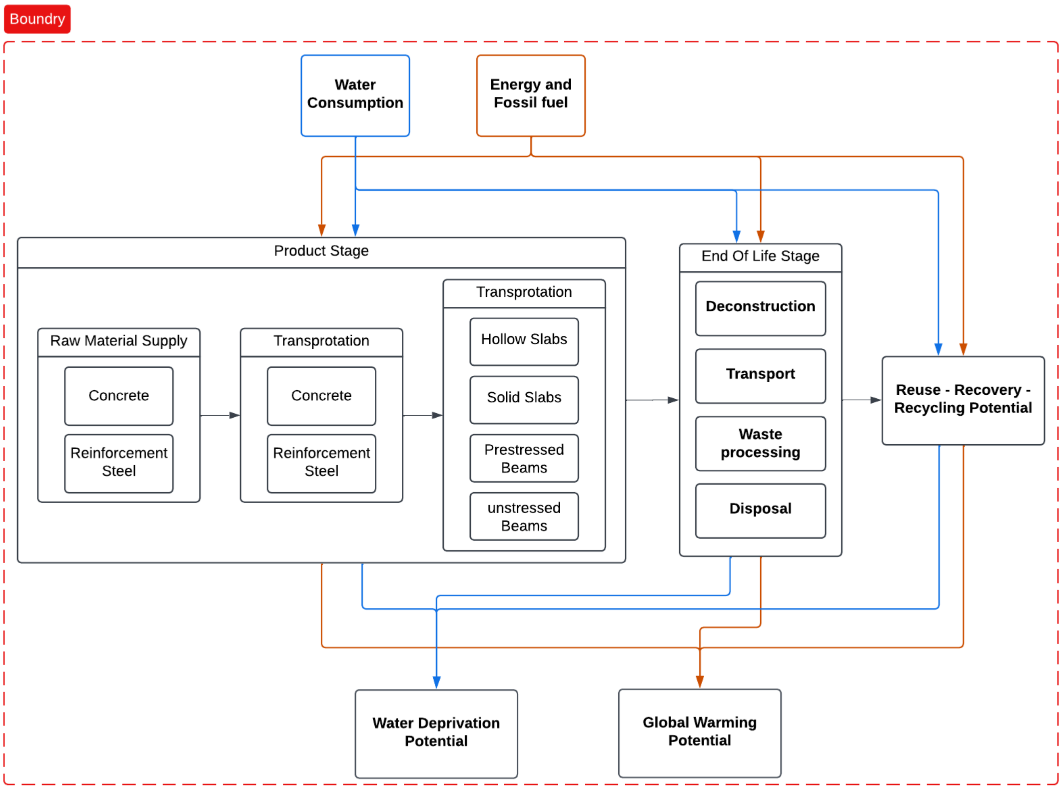


Figure 3: Goal and Scope

The resource for the environmental impact of each component type is Environmental Product Declaration (EPD) report. This report is a verified document published by producers that quantifies all environmental inputs and outputs for a certain product. The products used for this study are taken from different manufacturers, all in the EU region, although the ideal comparison would be made between different products produced by the same manufacturer. The resulting **Life Cycle Inventory** (LCI) is shown in *Table 1*.

All EPD's share the functional unit of "1 ton of average precast concrete elements", and the reports cover different dimensions of these elements and different concrete grade.

Table 1

Component	**Scope**	**GWP** kg CO_2 eq./t	**WDP** m^3/t	**Resource**
Concrete Beam	CB	297.08	257.8	[3]
Prestressed Beam	PB	255.97	254.1	[4]
Solid Floor Slab	SF	179.226	51.81322	[5]
Hollow core slab	HF	188.03	25.56	[4]

III. Life Cycle Timeline

To determine the interventions required to maintain each design, multiple resources were referred to in order to estimate maintenance frequency through the total lifespan of the substructure. *Shannag et al.* [6] represented a case study of repair and maintenance of a precast concrete structure composed of solid floor slabs, aiming to extend the service life of this structure. *Takewaka et al.* [7] introduces essential concepts of maintaining the concrete structure, along with recommendations for maintaining them. A research report for deterioration of prestressed concrete bridge beams [8] is referred to compare prestressed concrete deterioration, while [9] compares the long-term deterioration mechanisms of solid versus hollow-core slabs. These resources were used to define essential maintenance events, estimate and assume their frequency for different components, which are shown in *Table 2*.

Table 2

Design Option	Maintenance event		Frequency	Total lifespan
1- Concrete beam with Solid floor slab	Visual Inspections	VI	2	150
1- Concrete beam with Solid floor slab	Sealing Cracks	SC	8	150
1- Concrete beam with Solid floor slab	Protective Sealing	PS	10	150
1- Concrete beam with Solid floor slab	Major Rehabilitation	RP	25	150
2- Prestressed beam with Solid floor slab	Visual Inspections	VI	1	150
2- Prestressed beam with Solid floor slab	Sealing Cracks	SC	5	150
2- Prestressed beam with Solid floor slab	Protective Sealing	PS	10	150
2- Prestressed beam with Solid floor slab	External Post tensioning	EPT	30	150
3- Concrete beam with Hollow core slab	Visual Inspections	VI	2	150
3- Concrete beam with Hollow core slab	Sealing Cracks	SC	6	150
3- Concrete beam with Hollow core slab	Protective Sealing	PS	8	150
3- Concrete beam with Hollow core slab	Major Rehabilitation	RP	20	150

The interventions needed within the lifespan of the selected system for each design option is plotted to create better understanding of each system's requirements. As per the previous assignment, maintenance activities play an important role in ensuring the system reaches its maximal lifespan, while also contributing to different resource consumption, and in this assignment, the associated resources are the environmental ones reflected in GWP and WDP values.

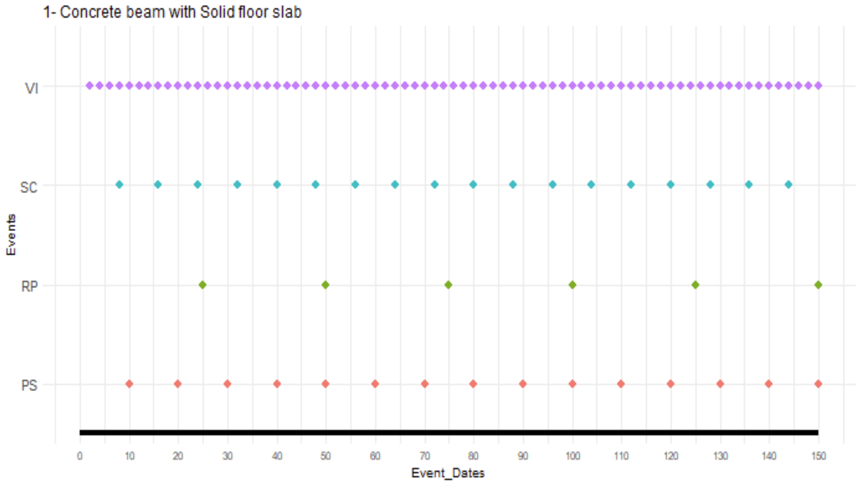


Figure 4

Figures 4, 5 and 6 show the intervention timeline for the first, second and third design options respectively, offering a better understanding of each system's needs. It can be noted that Major

Rehabilitation is noticeably more occurring in both the first and third design options, both made from non-Prestressed beams, while a parallel action for prestressed concrete is to perform external post tensioning.

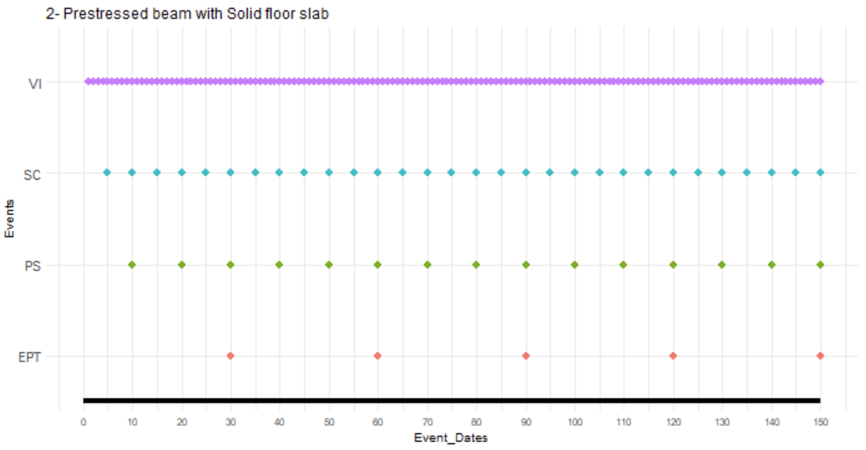


Figure 5

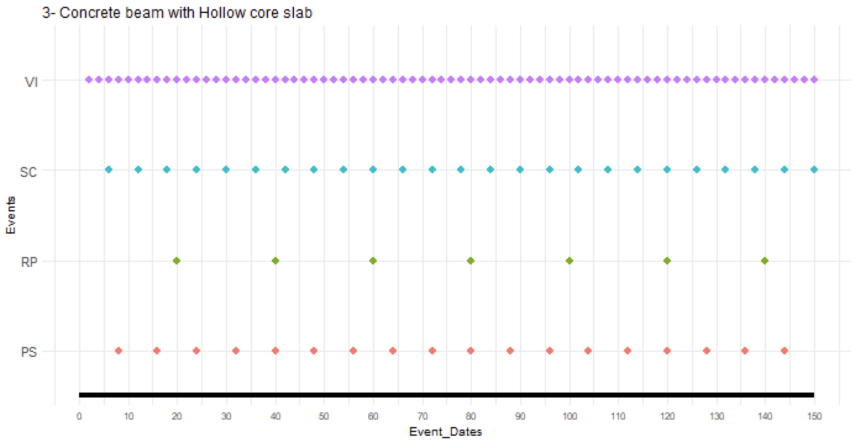


Figure 6

IV. Life Cycle Inventory and Analysis (LCI)

The inventory defined in the goal and scope section is then used to perform Life Cycle Analysis for the Precast Floor subsystem. To analyze the environmental impact of each design option, the design was standardized by determining a design case of a 6 m span beam with 3 m span spacing between the two beams. The design is then completed by using rules of thumb to calculate preliminary beam depth and floor slab thickness, shown in *Table 3*.

Preliminary Dimension	function
Reinforced Concrete Beam Depth	Span / 15
Precast Concrete Beam Depth	Span / 20
Solid Floor Slab Thickness	Spacing / 28
Hollow Floor Slab Thickness	Spacing / 22

Table 3

Additionally, hollow core slab variations produced by the referred EPD report are noted to have opening with a height between 0.5 to 0.6 of the total slab thickness, which is then estimated by decreasing the total volume of the hollow slab by 40% , counting for concrete between voids.

After calculating each component third dimension, volumes are calculated accordingly, then weight of each required component. This gives us the quantities that can be multiplied by GWP and WDP derived from the EPD reports, which are measured per ton. For each design option, GWP and WDP values for their components are summed to the final value that will compare their monitored environmental impact.

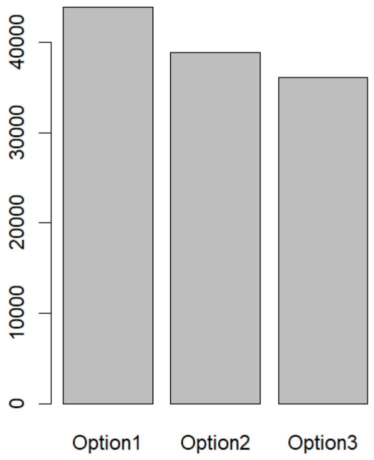


Figure 7: GWP

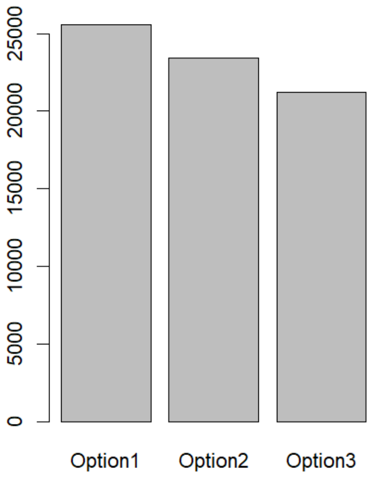


Figure 8: WDP

Results show the close impact of the three options for our chosen design, while in greater scale comparison this impact will grow to be more significant. Option 3 shows primacy upon other options as it holds the least GWP and WDP values, followed by the second then first options. Resulting values are shown in *table 4*.

These results reflect how hollow slab design significantly reduces the quantities of concrete needed while obtaining good load resistance. Furthermore, precast prestressed concrete beams serve as a good structural choice despite the added manufacturing complexity, as it also reduces the amount of material used for beams. Solid core slabs with regular reinforced beams represent the least environmental efficiency by requiring the most material to support loads.

	GWP	**WDP**
Option 1	43884.13	25580.34
Option 2	38881.11	23397.09
Option 3	36126.85	21217.15

Table 4

V. MCDM - AHP

To further evaluate the acquired results and conclusions, Multi Criteria Decision Making problem is formed, using Analytic Hierarchy Process (AHP). AHP provides a means of decomposing the problem into a hierarchy of sub-problems which can more easily be comprehended as subjectively evaluated [10], the lowest level being our design options, and the selected environmental impact criteria is the one above.

A matrix is created to represent comparisons between different design options. Ratios are calculated depending on results in *table 4* using function $a_{ij} = \frac{impact_j}{impact_i}$, creating an outcome score matrix that defines weights for options regarding their effect on GWP and WDP.

$$\boxed{\begin{matrix} 1 & 0.89 & 0.82 \\ 1.13 & 1 & 0.94 \\ 1.22 & 1.07 & 1 \end{matrix}} \qquad \boxed{\begin{matrix} 1 & 0.91 & 0.83 \\ 1.1 & 1 & 0.91 \\ 1.21 & 1.1 & 1 \end{matrix}}$$

GWP comparaison matrix WDP comparaison matrix

The values in the matrices are then approximated as follows:

ratio ≤ 1.2 → 1

1.2 < ratio ≤ 1.4 → 2

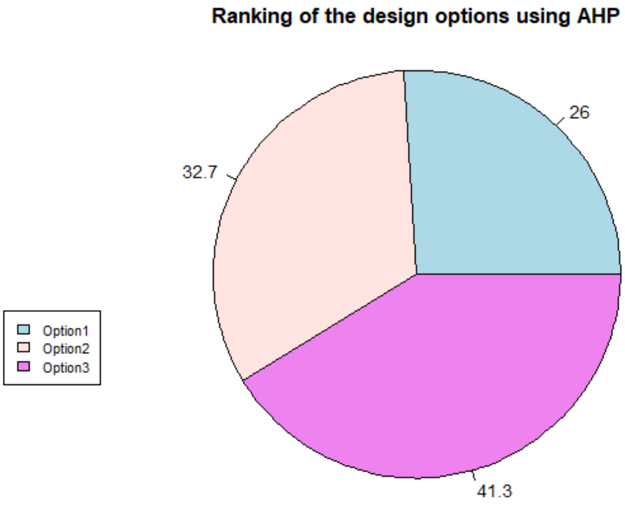
Resulting in the following score matrices:

$$\boxed{\begin{matrix} 1 & 1 & 1/2 \\ 1 & 1 & 1 \\ 2 & 1 & 1 \end{matrix}} \qquad \boxed{\begin{matrix} 1 & 1 & 1/2 \\ 1 & 1 & 1 \\ 2 & 1 & 1 \end{matrix}}$$

GWP score matrix WDP score matrix

On the next hierarchical level, score matrix is defined to represent pairwise comparison between the studied impact criteria, GWP and WDP, the weights are assigned reflecting how global warming potential is generally considered the primary and most important metric, due to its role as the main driver of climate change, while water deprivation potential has a localized importance reflected when projects are located in water-severe environmental and social sequences [11]. According to these factors, along with the EU increasing attention towards global warming potential reflected in construction sustainability assessment and regulations, GWP factor is suggested to be 3 times as important as WDP in our assessment.

The results of the AHP analysis is plotted in *figure 9*. These results support the results of the previous lifecycle inventory analysis, showing that the best option is the third, followed by the second then the first.



VI. Analyzing results and discussion

The LCA results show that the three precast alternatives have different environmental performances driven mainly by differences in material quantities. Option 3, which uses a hollow-core slab with a reinforced beam, achieves the lowest GWP and WDP values. This is primarily due to the reduced concrete volume in the hollow-core slab, which lowers manufacturing impacts and resource use. Option 2 performs better than Option 1 because prestressing allows for a smaller beam cross-section and therefore less material demand, even though the slab remains solid. Option 1 has the highest impacts since both components are fully solid and use the greatest amount of concrete.

These results are conducted using very limited inputs (represented in the number of variables considered and the scale of the subsystem) and approximate values (both for maintenance interventions and structural design dimensions), thus reflecting the huge improvement possibilities for developing this model into an accurate more reliable one. Nevertheless, this analysis reflected how structural design decisions can make a significant environmental footprint.

The Analytic Hierarchy Process is one of many Multi-Criteria Decision Processes, deepens the understanding of each factor contribution to the overall conclusion. The analysis underscores the importance of evaluating whole-system behaviour. Prestressing improves environmental performance through material reduction, but its benefits, for the case of our used components, depend on manufacturing processes, tensioning systems, and potential maintenance requirements over the lifespan. This reflects the need for holistic design choices that balance structural behaviour, durability, and sustainability.

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