Whole Life Civil Systems Analysis

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

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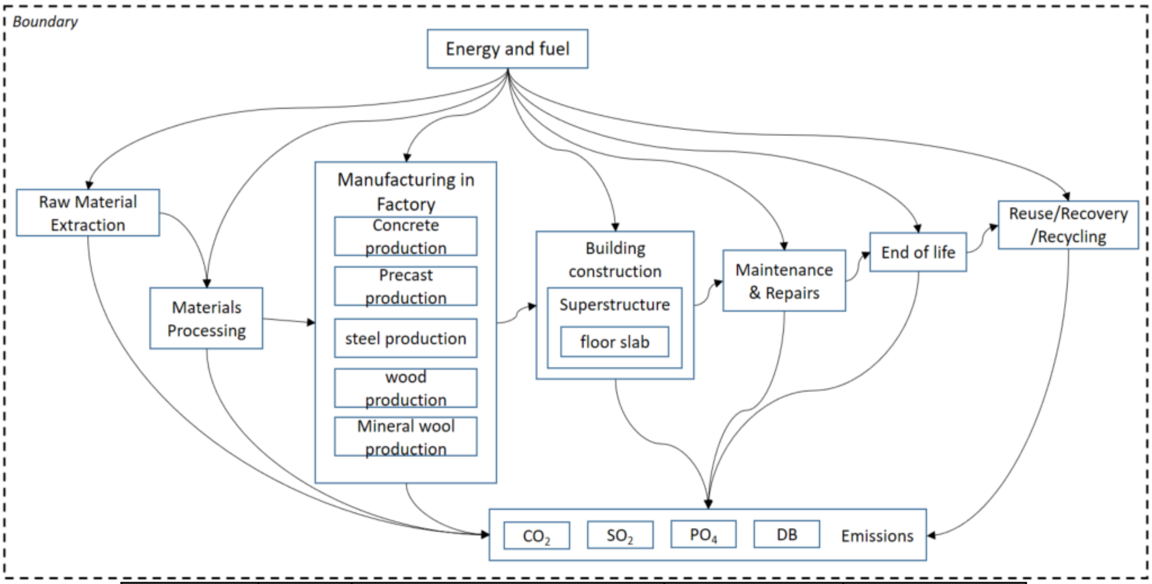
1. Introduction

In the previous assignment, the deterioration of the system, a community multipurpose building, over its lifetime was analysed using Markov chain for deterioration modelling, fault tree for failure analysis, MTTF, and MTTR. In this assignment, the objective is to select a building subsystem option by assessing life-cycle impacts and utilizing Multi-Criteria Decision-Making method AHP.

2. Subsystem for a Community-Multipurpose Building

The use of Life Cycle Assessment (LCA) to understand environmental impacts can significantly facilitate decision-making when selecting a design option, provided that the chosen design minimizes environmental impact throughout its lifetime. As a subsystem a slab is chosen. This assignment analyses the LCA of the following in Table 2-1 three composite slab options, with the third being the most conventional.

2.1 Goal and Scope of the LCA



Product stage			Construction stage		Use stage							End of life				Benefit and loads			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw Material Extraction	Transport	Manufacturing in Factory	Transport to Site	Installation and Erected Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operation Energy Use	Operation Water Use	Demolition	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling	Landfill
X	X	X	X	X								X	X	X	X	X	X	X	X

Figure 2-1: System boundary, upper figure self-generated, bottom figure excerpt from [1, p. 5]

In this analysis, the scope extends from cradle to grave, encompassing the marked categories presented in the figure above. The functional unit for all elements, except for reinforcement, is m³, whereas for reinforcement, it is kg. The objective is to conduct an ecological footprint analysis, considering energy, CO_2, PO_4, and SO_2 as criteria and the design options as the alternatives.

2.1.1 Description of the chosen subsystem design options

Three possible slab design options are shown in Table 2-1. Material and dimensions are provided in Table 2-2.

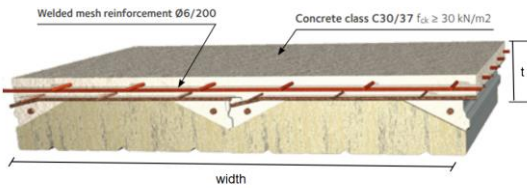
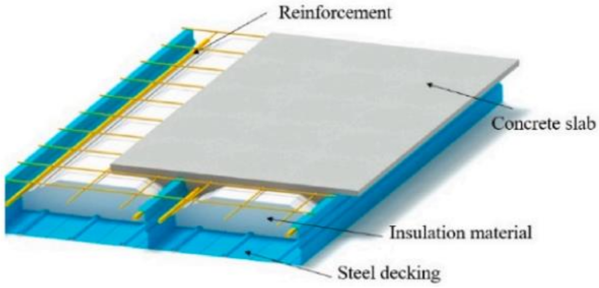
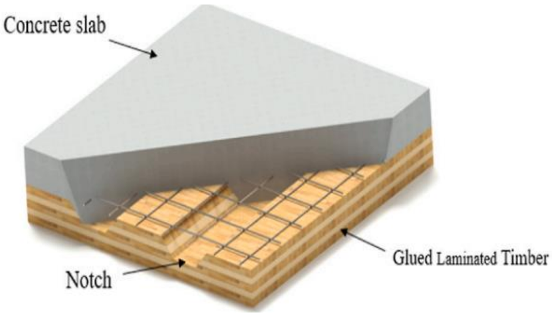
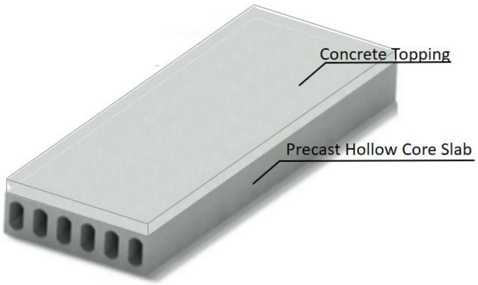
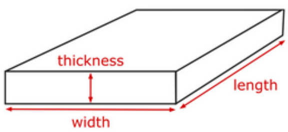
Design option 1: ***Cofradal 200 slab composite*** Prefabricated composite slab
 
Design option :2 ***Glued laminated timber (GLT)-concrete slab***

Design option 3: ***Precast reinforced hollow core***

For all slabs: 

Table 2-1: Slab Design options, self-generated with excerpt from [1, p. 3] and modified

design option	material	thickness & dimension [mm]
1	Reinforcement bars	10
	Reinforcement mesh	Ø6/200
	Mineral wool with density 50 kg/m³	thickness:200
	Steel metal deck	thickness:0.88; width: 1200
	Concrete	150
	Shear connectors	19 x 95
2	Concrete C30/37	thickness:64
	Reinforcement Mesh Ø6/200	200 x 200
	Screws	-
	Glue laminated timber	thickness:90; width:600
3	Hollow core slab	thickness:200
	Steel trimmer – Plate and bracket welded	1200 x 10
	Concrete topping C45/55	50

Table 2-2: Slab Design option parameter, self-generated with excerpt from [1, p. 3f., Table 1, p. 6], [3, p. 1092]

The table above contains the dimensions of the design options elements. For simplification, the analysis will not consider connectors such as screws, shear studs, and steel trimmers. All slabs have a span of 7 m and support a live load of 2.5 kN/m² over a 50-year period [1, p.5].

Now that we have the dimensions of each slab design option, the floor plan will be presented to establish the basis for quantity computations of materials. In Assignment 1, a floor area of about 400 m² was considered. To avoid rounding and only consider complete slabs, this has been extended to 420 m² without considering any openings in the slab.

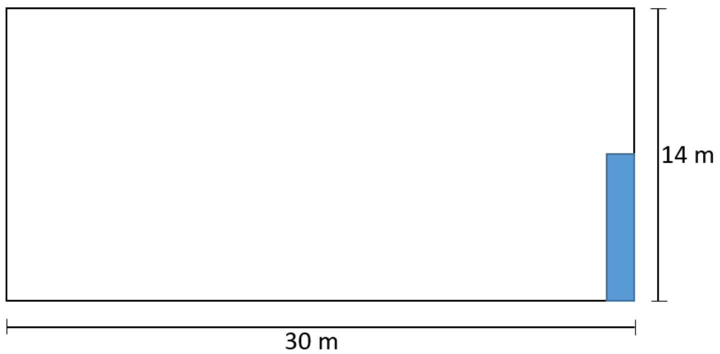


Figure 2-2: floor plan with slab element (Option 1 or 3), self-generated figure

If a beam is placed at $\frac{14\,m}{2} = 7m$, the quantities presented in Table 2-4 are computed, taking into account the dimensions of the slab design option. An example is provided for design options 1 and 3 in the figure above. For design 2, twice the number of slabs is needed compared to options 1 and 3, due to width variation.

2.2 Life Cycle inventory (LCI)

The environmental indicators based on the slab materials were collected using the sources listed in the table below.

material	energy	CO2	PO4	SO2	functional unit	source
Reinforcement mesh	2.43	225	-	1.85	kg	[2]
Concrete C30/37	1179.9	224.29	0.0695	0.356	m^3	[9]
Mineral wool with density 50 kg/m^3	915.91	63.32	-	-	m^3	[11]
Steel metal deck	138.12	6.2	0.0019	0.00914	m^2	[12]
Concrete C30/37	1179.9	224.29	0.0695	0.356	m^3	[9]
Reinforcement Mesh	2.43	225	-	1.85	kg	[2]
Glued laminated timber	-1754.6	-898	0.1976	0.73	m^3	[8]
Hollow core slab	442	75.2	0.0514	0.276	m^2	[13]
Concrete topping C45/55	1955.96	315.89	0.106	0.506	m^3	[10]

Table 2-3: environmental indicator values for design option materials, self-generated table

Similar to the tutorial, the composite elements and the reinforcement are considered separately. The composite elements include all design option elements except the reinforcement. The environmental indicators for the reinforcement were taken from the assignment tutorial and, therefore, do not include stages C and D of the set system boundary. As a simplification, these values are still used.

To simplify the R implementation and address vector creation issues caused by diverse scopes of composite elements, they were combined into a single entity. It's essential to recognize that each element has unique volume, environmental values, and functional units. Standardizing functional units, as explained in Section 2.1, involves calculating a correction factor (considering equivalent thicknesses and material density for reinforcement) to aggregate element values, as shown in Table 2-4.

Two critical steps in computing the final values for the LCI will be briefly outlined. Concerning the hollow core slab, an additional assumption was made, and an equivalent thickness of the slab was calculated, encompassing only the concrete volume by deducting the hollow cores. The material for the slab itself and the concrete topping above it were selected to be identical. For design option 3, and in the LCI calculation, a thickness of 0.173 m will be considered, with an additional reinforcement taken into account to partially offset the required reinforcement in a hollow core slab.

In the case of design option 1, the concrete volume was computed using information from [14, p.20f.], and an equivalent thickness was also determined, resulting in the complete composite having an equivalent thickness of 0.30088 m.

An explanation of the quantities is provided in Section 2.1.1.

Material	Scope	quantities	energy	CO2	PO4	SO2
Reinforcement mesh	RCWSD	50	2.43	225	-	1.85
Composite SteelConcreteWool	RCWSD	50	1179.9	224.29	0.0695	0.356
Composite ConcreteGLT	RCGLT	100	5060.237	-302.578	0.3407	1.573
Reinforcement mesh	RCGLT	100	2.43	225	-	1.85
Composite HCSlabConcreteTopping	PRHCS	50	1955.96	315.89	0.106	0.506
Reinforcement mesh	PRHCS	50	2.43	225	-	1.85

Table 2-4: final values for the LCI, self-generated table based on Table 2-3

scope	Definition
RCWSD	Reinforced Concrete, Wool, Steel deck
RCGLT	Reinforced Concrete, Glued laminated timber
PRHCS	Precast reinforced hollow core slab

Table 2-5: Legend for table 2-4, self-generated

3. Life Cycle timeline

Every design option requires material dependent interventions with specific frequency which as mentioned are going to be encountered in the LCA later on. The following table contains basic interventions for given event examples.

Design option	Example Event	Needed maintenance	Reference for frequency
1. Cofradal 200	Prevent/Slight corrosion of the steel decking	Coating	[7]
	Corrosion of the steel decking	Deck replacement	[7]
	Cracking in the Concrete	Repair –sealing of cracks	Assumption 1
2. GLT-concrete slab	Treatment & Prevention of Mould and Insects in the GLT	Coating	[4, p. 89]
	Cracking in GLT	Checking & Delamination - replacement	[5, p.5] & assumption 3
	Cracking in the Concrete	Repair –sealing of cracks	Assumption 2
3. Precast reinforced hollow cast	Cracking in the Concrete	Repair –sealing of cracks	Assumption 4
	Maintenance	Inspection	Assumption 5

Table 3-1: Intervention for the three Design options, self-generated table

The frequencies of needed interventions, were set according to the references in the table and the described assumptions in Table 3-4.

Design option	Event	Frequency	Total Lifespan
1. Cofradal 200	M	5	50
	DR	1	50
	R	5	50
2. GLT-concrete slab	M	10	50
	PR	2	50
	R	6	50
3. Precast reinforced hollow cast	M	8	50
	R	4	50

Table 3-2: final Data for the Life Cycle Inventory Analysis, self-generated table

event	Definition
M	maintenance
DR	deck replacement
R	repair
PR	partial replacement

Table 3-3: Legend for Table 3-7, self-generated table

nr.	made assumption	Description
1	Cracking of concrete	Based on recommendations from [6, p. 5], concrete structures typically undergo close-up inspections every 6 years. However, not every inspection reveals cracks. Considering practical insights, I have assumed a repair interval of 10 years for addressing concrete cracks.
2	Cracking of concrete of design option 2 Using assumption 1	Taking into account Assumption 1 and acknowledging the distinct swelling and shrinking behaviours of wood and concrete it is recognized that this could naturally elevate the probability of crack formation in concrete. Therefore, the initially assumed occurrence interval is adjusted to 8 years. For rounding purposes, this is extended to 8 years and a quarter (8.333).
3	Frequency of checking & delamination	According to [5, p. 5], a bridge incorporating Glued Laminated Timber (GLT), also known as glulam, has been reported to be "still giving good service after 40 years"[5, p. 5]. Given that the loads on a flooring slab and a bridge are comparatively smaller, along with shorter spans, I deduced that if delamination occurs, replacement or delamination repair may be necessary a maximum of twice within a 50-year lifespan, especially when considering slab components.
4	Cracking of concrete of precast hollow core slab Using assumption 1	Taking into account Assumption 1 and the fact that the hollow core slab has a higher concrete quality, thereby increasing the concrete strength and already reducing the likelihood of crack formation, the assumed interval from Assumption 1 is extended from 10 years to 12 years. For rounding purposes, the 12 years are extended to 12.5 years.
5	Maintenance of the precast hollow cast slab	According to [6, p. 5], the inspection interval for concrete structures for a close-up inspection is 6 years. Regarding the hollow cast slab, this is particularly important because in the hollow areas, the concrete thickness is much thinner than in the rest of the slab. For rounding purposes, the 6 years were extended to 6.25 years.

Table 3-4: Made assumptions regarded in the LCI for Table 3-6 & 3-7, self-generated table

Using the Shiny app the needed interventions for each design option over its lifetime from Table 3-2 are being visualised.

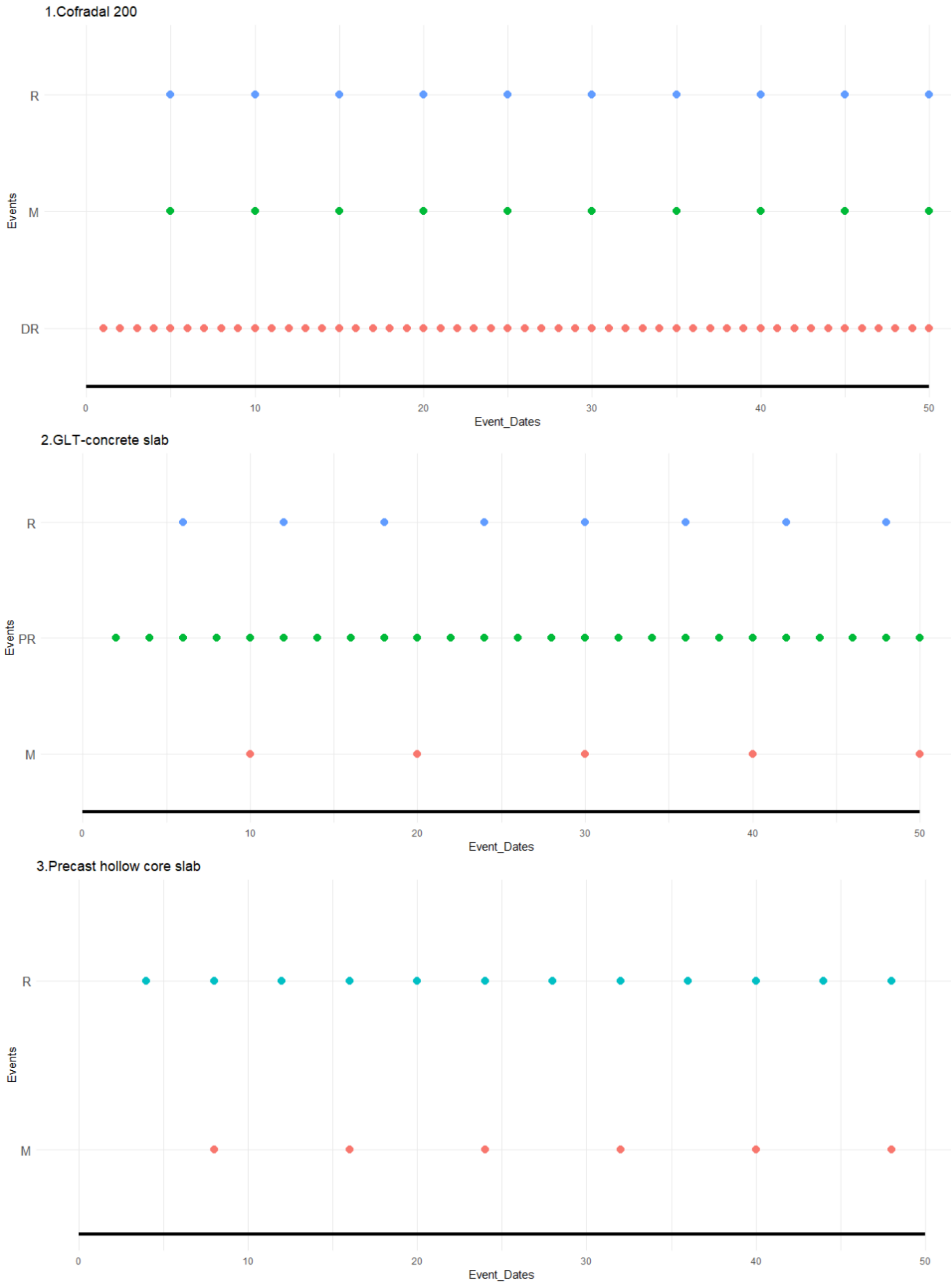


Figure 3-1:Visualisation of design option specific interventions , excerpt from Shiny app

4. 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 slab 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 barplots.

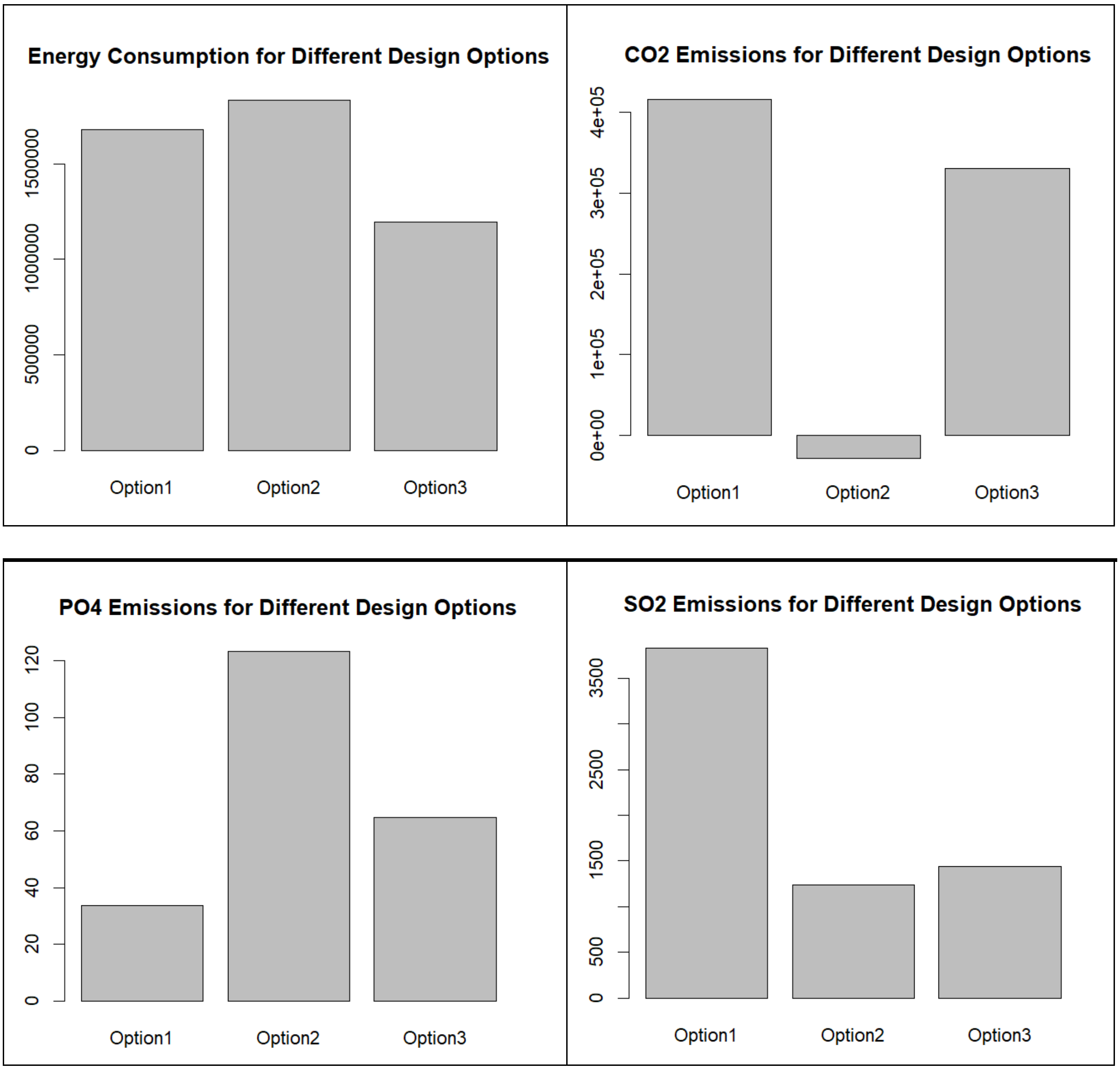


Table 4-1: Barplots for the resulting environmental indicators of each design option, excerpt from [15]

The environmental indicator that exhibits the most variation among the three design options is carbon emissions. Option 2 has the lowest, even a negative value, possibly influenced by the bio-chemical behaviour of wood over its lifetime and the very good recycling properties. Simultaneously, Option 2 shows the highest PO_4 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 slabs based on ecological emissions depends on the weighting of the categories. This aspect will be further investigated using a Multi-Criteria Decision-Making method.

5. MCDM – Analytic hierarchy process (AHP)

he AHP is employed for ranking slab options by assigning relative weights to criteria and alternatives, converting subjective assessments into ratio scales. The principal eigenvector, associated with the largest eigenvalue, plays a crucial role in determining stable and consistent values for maintaining the ratio scale of comparisons. After deriving the principal eigenvector, normalization is applied to ensure that the weights sum up to 1 [2, p. 13ff.].

The pairwise comparison of alternatives is facilitated using barplots in Table 4-1, with Saaty's scale used for weighting.

Degree of Importance	Scale	Definition
1	Equal importance	The two activities contribute equally to the goal
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	One activity is strongly favored over another; the element is very dominant, as shown in practice
9	Extremely important	The evidence is in favor of one activity over another to the greatest possible extent
2, 4, 6, 8	Intermediate values between two judgments	They are used to express preferences that are between the values of the above scale
Reciprocal values	If activity i has one of the above numbers, by comparing i to j, the inverse of i concerning j is obtained.	

Figure 5-1: Criteria Priority Weight for Research Metric, excerpt from [16, p. 6]

The alternatives where weight like the following:

```
energy <- t(matrix(c(1, 2, 1/4,
                     1/2, 1, 1/5,
                     4, 5, 1),
   CO2 <- t(matrix(c(1, 1/9, 1/4,
                     9, 1, 8,
                     4, 1/8, 1),
   PO4 <- t(matrix(c(1, 8, 4,
                     1/8, 1, 1/6,
                     1/4, 6, 1),
   SO2 <- t(matrix(c(1, 1/7, 1/6,
                     7, 1, 2,
                     6, 1/2, 1),
```

Table 5-1: matrices-pairwise comparison of alternatives AHP, excerpt from [15]

The matrices are now bundled in a list.

In the next step, the pairwise comparison of the criteria is conducted. The indicators are weighted using the scale in Figure 5-1 and the list of key indicators in [17]. Since CO_2 is the main key indicator according to the organisation for economic and co-operation (OECD) [17, p. 8], it will be assigned the highest weight, followed by SO_2 and energy based on their ranking. Since PO_4 is not considered a key indicator, it will carry the least weight. The weight value was chosen according to the ranking in [17, p.8].

```
# pairwise comparison of the criteria
CWPC <- t(matrix(c(1, 1/2, 5, 1/3,
                   2, 1, 9, 4,
                   1/5, 1/9, 1, 1/5,
                   3, 1/4, 5, 1),
```

Figure 5-2: : matrices-pairwise comparison of criteria AHP, excerpt from [15]

With this matrix the following pie chart is obtained.

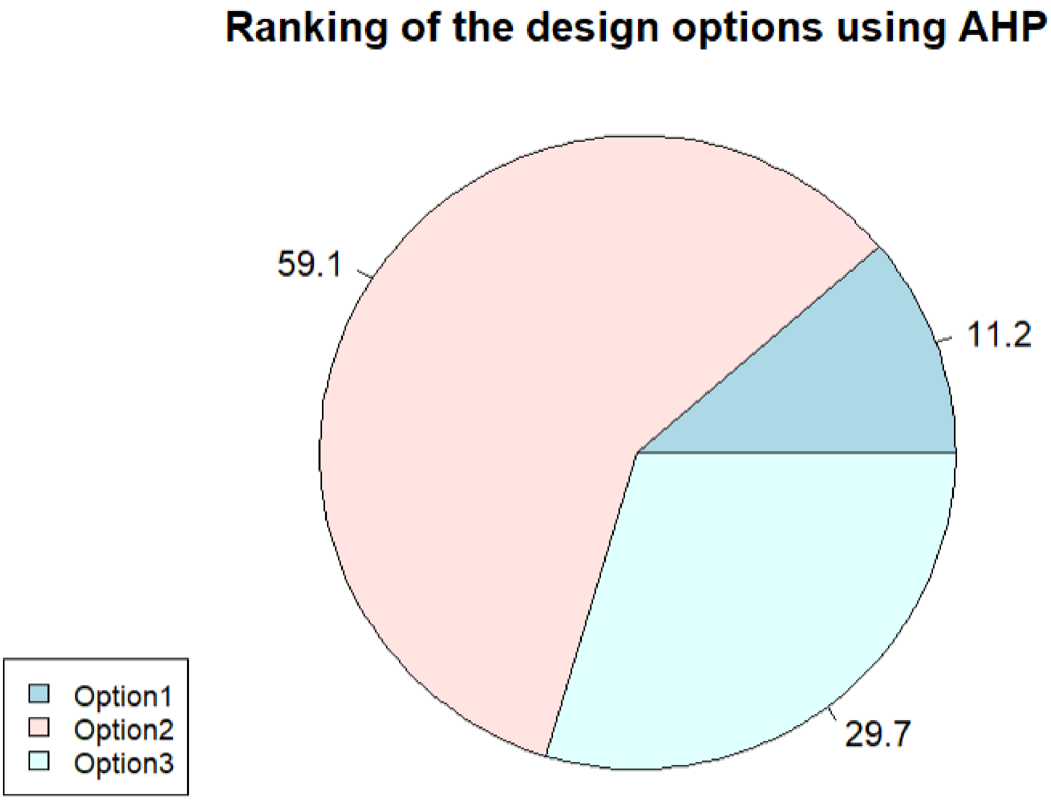


Figure 5-3: Ranking of the design options using AHP , excerpt from [15]

Regarding the results, it seems that Option 2 – the GLT concrete slab is the most favourable choice. This is likely because CO_2 was highly prioritized in the pairwise comparison of the criteria. The precast hollow core slab appears to be a better option than the Cofradal slab. While the results are satisfactory based on the current ranking and scope, they can change when specific or varied goals are considered. For instance, if the ranking incorporates the distribution on the barplots for the four criteria, the second design would emerge as the best. In conclusion, using the information provided in the assignment and considering the set goal and scope, the "best" option depends on the weighted criteria. This underscores the multi-criteria nature of the decision problem. At this point, applying sensitivity analyses would be very useful.

6. LCA comparison with reference

The references used, particularly [1], include a Life Cycle Assessment (LCA) for the chosen design options in this assignment, among others. It's important to note that only the materials and their dimensions were considered in this assignment, with quantities and environmental indicators computed and researched separately. The results of both analyses exhibit significant variations, likely attributed to differences in computation methods for quantities and environmental indicators, which may vary between countries. Since I primarily considered environmental indicators set by the German government, discrepancies with references from Malaysia are evident.

Further investigation and research are warranted to comprehend the source of these differences and assess their impact on decision-making processes for the same design options.

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ALL SOURCES WERE LAST OPEND ON 18 January 2024

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