Whole Life Civil Systems Analysis

Individual Project 2

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Introduction

Construction industry consumes about 50% of all non-renewable resources, according to previous report[1], 45-50% of energy, 50% of water resource and 60% of timber used for buildings. Besides, the building and construction sector is the largest end-market for chemicals, producing 1 kg of textiles requires 0.58 kg of various chemicals on average[2], which left significant amounts of pollution worldwide.

The life cycle analysis not only discover multiple external impacts of construction, but also provides insights toward building maintenance. This assignment aims to analyze the environmental influence such as climate change or air pollution caused by different structure systems from cradle to grave, including RC, SC and GLT. Moreover, the impact of global warming could be seen as the most profound among all the other environmental pollution in this century, this project particularly emphasize the sectors of greenhouse gas emission.

1.1 Greenhouse gas emission

According to research in 2022[3] buildings were responsible for 34% of global energy demand and 37% of energy and process-related carbon dioxide (CO*2)* emissions, which is the largest emitter for global emissions. Buildings and construction industry contributes about 21% of global greenhouse gas emissions, which grows more than 30% of the amount in 2019[4]. In a report published by Forbes[5] evens indicates that the construction sector is responsible for 40% of global carbon emissions and similar proportion of energy usage.

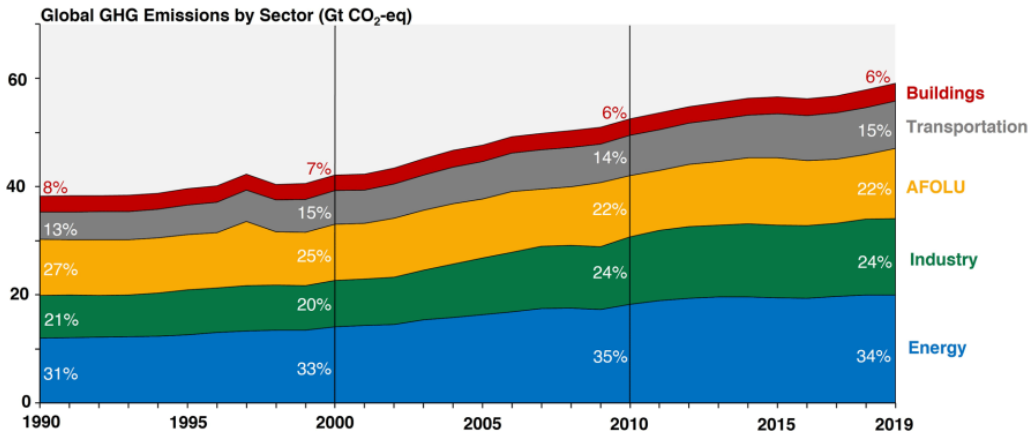

Figure 1 Global GHG emissions by sectors (Gt CO2-eq)[6], Note: Emissions from Building sector are 16% when electricity use in buildings is included in this sector instead of the Energy sector

1.2 Air pollution

Threats caused by air pollution is becoming increasingly important in recent years, meanwhile, huge amount of pollutants such as nitrogen oxides(NOx) or sulfur dioxide(SO2) are produced during the building life cycle.

In fact, prior report[5] shows that almost a quarter of air pollution is created by construction companies. Moreover, 99% of global population was living in places that the WHO air quality guidelines level were not met and 4.2 million premature death due to outdoor air pollution in 2019.[7]

Besides, it also cause environmental hazard includes acid rain, regional haze, soil acidification, coastal eutrophication, which will damage both our natural ecosystem and architectural structures. For example, prior research has shown that acid rain causes annual economic losses in excess of 0.3 billion € in Taiwan.[8]

1.3 Goal and Scope of the assessment

The goal of this report aims to provide useful information for future projects selecting the most suitable and also eco-friendly structural system, by figuring out the amount of energy consumption and chemical pollutants created during the life cycle of beams, including CO2, CH4, Nox and SO2.

To have a thorough understanding of environmental impact within these design options, I refer to the previous research[9] regarding the life cycle of buildings to define the boundary and scope that covers from cradle to grave in a 100-year lifespan, which is a common service life of these types of structural systems.

Building life cycle																Supplementary information
Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction Demolition	Transport	Waste processing	Disposal	Re-use- Recovery- Recycling- potential

Table 1 Building life cycle stages[9]

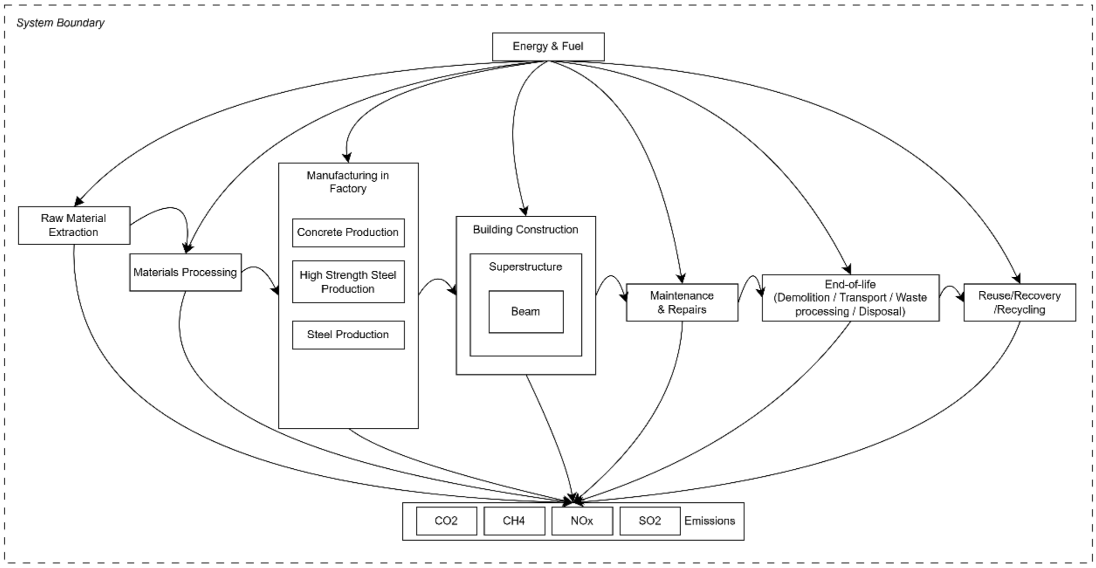

Figure 2 Scope & boundaries of the assessment

1.4 Challenges & Limitations

The major challenges and limitations of the assessment lay in lack of data (mainly for diversity of resources and recorded chemicals) for life cycle inventory of different materials, especially some of them only have that of cradle-to-gate period. Besides, situation could be differed due to regional factors, including geographical or cultural issues. For example, in some Asian countries, the carbon tax system and the concept of ESG might not be well-accepted by the authorities or the industry compares to other Europe countries, thus makes different in their production methods or the life cycle inventory data of materials. With that, the fact that some of my background settings are based on my prior professional experience, including the 4.8m span and those chosen structure systems, could also makes different within the results compare to others with different contexts.

Methods

2.1 Design options

To cover the most common structural types for residential buildings, I propose 3 options toward beam design and refer to specification data[10][11][12], making sure that all options have a span of 4.8 m(16ft) and support a basic live load(2.4 kN/m2) for a < 3 story residential buildings. The critical information each option is listed in Table 2, including description, material and dimension.

Design Options	Description	Material	Dimension
Option 1	RC Beam	5000 psi concrete, S355 Steel(rebar)	30.48cm*40.64cm, rebarØ=19.1mm
Option 2	SC Beam	S690 Steel (W14x26)	49.6128cm2 (12.78cm*35.31cm)
Option 3	GLT Beam	Softwood lumber	33cm*6.5cm

Table 2 Beam design option specification

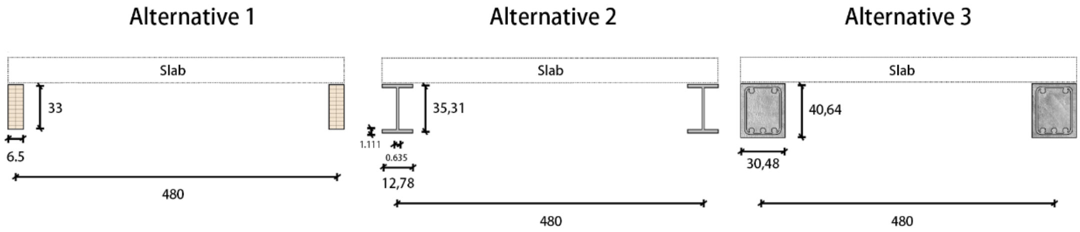

Figure 3 Dimensions of alternatives

2.2 Life Cycle Inventory(LCI)

I referred to the previous study in Table 3, to choose the major indicators adopted in the assessment, including energy(PERT+PENRT), CO2(GWP), CH4, NOx and SO2(AP).

Abbreviation	Indicator	Unit
GWP	Global warming potential	kg CO_2 eq.
PERT	Primary energy, renewable, total	MJ
PENRT	Primary energy, non-renewable, total	MJ
ODP	Ozone depletion potential	kg CFC-11
AP	Acidification potential	kg SO_2 eq.
EP	Eutrophication potential	kg PO_4^{3-}
POCP	Photochemical ozone creation potential	kg C_2H_4

Table 3 Indicators for calculating the ecological impacts[13]

Table 4 provides a summary about LCI for main materials of different structural system, meanwhile the quantities here represents the amount of materials consumed for producing 1 m^3 of reinforced concrete, 1 kg of steel and 1 m^3 of GLT. For example, per square meter of GLT requires 511 kg(423.73 board feet) of softwood lumber, 7.73 kg PRF and 1.43 kg MUF resin.

Material	Scope	Quantities	Energy (MJ)	CO2 (g)	CH4 (g)	NOx (g)	SO2 (g)
Portland Cement[14]	RC	335kg	1502.95 (1460+42.95)	137438	5.67	339.7	195.9
Natural	RC	712kg	58.375	327708	0.025	4014	-

Aggregates[14]			(36.9+21.475)				
Manufactured Aggregates[14]	RC	1187kg	32.375 (10.9+21.475)	199580	0.008	1270	-
S355 Steel[15]	RC	108.198kg	503.121*6	37039	82.068	124	88.03
S690 Steel[15]	SC	1kg	27.9	2054	4.551	6.885	4.882
Softwood lumber[16]	GLT	511kg (423.73b.f.)	2153.724	191918	23.179	602.6	92.71
PRF Resin[17][18]	GLT	7.73kg	1.701	9507.9	12.213	28.6	10.97
MUF Resin[17][18]	GLT	1.43kg	0.156	2402.4	4.333	5.491	4.619

Table 4 Environmental impact indicator values for design options

Emissions to air (mass, g)

Cadmium (+II)	4.021E-005
Carbon dioxide	2054
Carbon monoxide	11.25
Chromium (total)	0.0002306
Dioxins (unspec.)	8.749E-010
Hydrogen chloride	0.06193
Hydrogen sulphide	0.08199
Lead (+II)	0.0009471
Mercury (+II)	5.985E-005
Methane	4.551
Nitrogen dioxide	0.03243
Nitrogen oxides	6.853
Nitrous oxide (laughing gas)	0.01518
NMVOC (unspecified)	0.31
Particles to air	2.315
Sulphur dioxide	4.882

Table 5 Chemical emission for 1 kg steel[15]

2.3 Life-Cycle Timeline

The lifespan of a ordinary RC, SC or timber-built residential buildings are around 100 years. Every design alternatives have different interventions with specific frequency overtime. For instance, reinforced concrete structures decay because artificial and environmental factors. Meaning regular inspection and maintenance is necessary for safety concerns, experts[19] suggest that this structure requires inspection at least every 4 to 6 years, for the analysis, I use the mean value of the range.

As for other structure systems, it's recommended to conduct inspection and cleaning at least every 2 year[20] for the SC structure, and to apply outdoor stain every 4 year for the GLT structure. Table 7 and Table 8 have summarize the intervention frequency and corresponding action for every design options.

Inspection	Inspection item
Structural safety	Member strength
Condition and durability	Concrete compressive strength, Crack width, Steel corrosion, Concrete carbonation depth, Concrete core test, etc.
Displacement and deformation	Horizontal displacement, Differential settlement

Table 6 Inspection items for RC structures[19]

Design Option	Event	Frequency(year)	Total Lifespan(year)
RC Beam	M	5[19]	100
RC Beam	PR	50	100
SC Beam	M	2[20]	100
SC Beam	MR	10[21]	100
SC Beam	PR	50	100
GLT Beam	M	4[22]	100
GLT Beam	MR	50[23]	100
GLT Beam	PR	50[23]	100

Table 7 Summary of the maintenance interventions for 3 design alternatives

Code	Event	Design Option	Action
M	Maintenance	RC Beam	Cleaning, Inspection
		SC Beam	Cleaning, Inspection
		GLT Beam	Apply outdoor stain
MR	Minor Repair	SC Beam	Sealant replication, Recoat
		GLT Beam	Connection Partial Replacement
PR	Primary Repair	RC Beam	Reinforcement measurement
		SC Beam	Beam Partial Replacement
		GLT Beam	Beam Partial Replacement

Table 8 Intervention and maintenance action of corresponding design option

Based on aforementioned reasons, we could further visualize the intervention timeline for better understanding and also organize the maintenance plan accordingly.

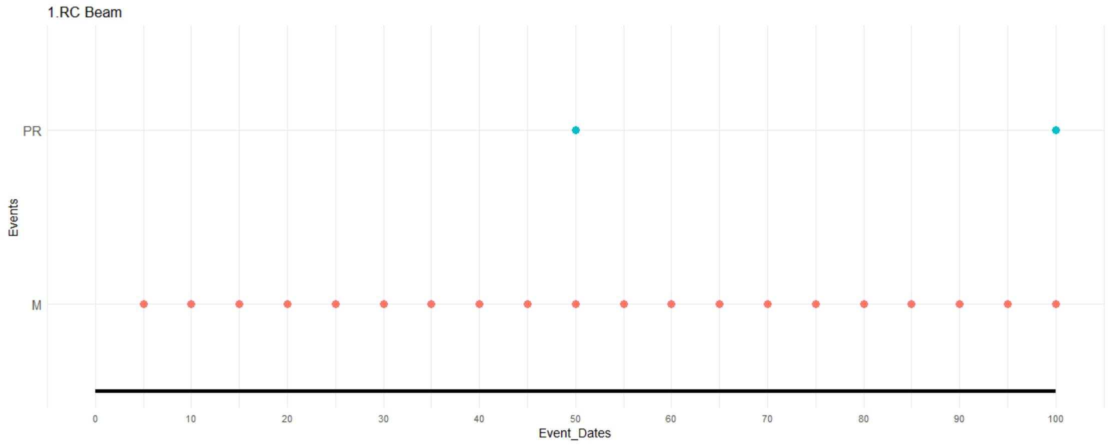

Figure 4 Maintenance interventions for RC beam system during building's life span

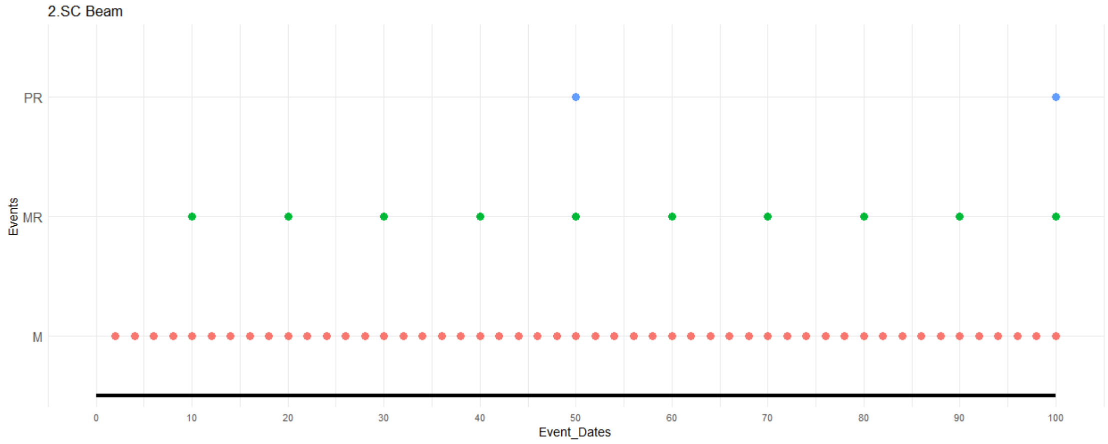

Figure 5 Maintenance interventions for SC beam system during building's life span

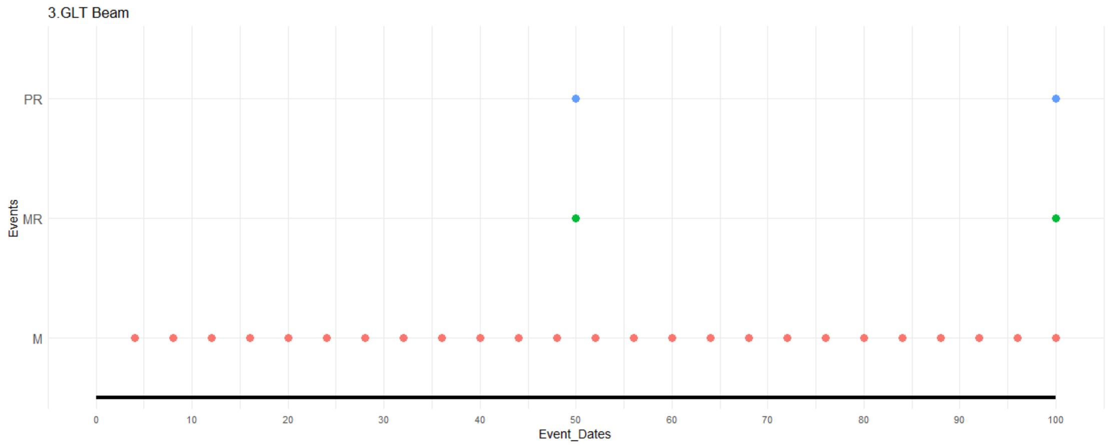

Figure 6 Maintenance interventions for GLT beam system during building's life span

Result and Discussion

4.1 Life Cycle Cost Analysis (LCC)

Life cycle cost is used to assess the overall costs during the entire lifespan of certain product, work or service. For construction projects, it usually includes materials (material production), construction, maintenance and demolition(end of life).
Based on the previous study[24], it's common practice to estimate the construction cost from the material costs, while the construction costs of all buildings were estimated equally as 150% of the materials' costs of the conventional alternatives.
On the other hand, according to the content, the difference between construction and maintenance cost is less than 1%, so I assume that these cost are the same to simplify the analysis. Table 9 shows the costs of different structural system that calculated based on the recent year data[24][25][26], assuming that the price of the material type such as concrete strength in the research data is the same as the material type in this study. The total cost per unit material means the cost for 1 m^3 of reinforced concrete, 1 kg of steel and 1 m^3 of GLT, and the total cost per building area means the cost for beams required for a 4.8m*4.8m slab.

Items	**RC**	**SC**	**GLT**
Materials	307.01 €/m3	84.394 €/kg	932.4 €/m3
Construction	439.421 €/m3	126.591 €/kg	1398.6 €/m3
Maintenance	439.421 €/m3	126.591 €/kg	1398.6 €/m
Demolition	143.3 €/m3	1.5 €/kg	3316.92 €/m3
Total Cost (per unit material)	1329.152 €/m3	339.076 €/kg	7046.52 €/m3
Total Cost (per building area)	3161.146 €	253548.867 €	2902.039 €

Table 9 Life cycle cost for design alternatives

From Table 9, we could find that the RC beam has the lowest total cost with the number of about 3161€ per building area, representing as the most cost-effective option among all of these design alternatives, while the GLT beam represents as a moderate choice with a total cost of 2902.039€ per building area. On the other hand, the steel beam stands as the most expensive structural types. What needs to be mentioned is that these numbers are based on per unit of construction material and building area, more detail needs to be considered for a complete construction project.

4.2 Life Cycle Inventory and Analysis

Plots below compare the energy consumption and emissions of greenhouse gas(CO_2, CH_4) and other air pollutants(NO_x, SO_2). It’s obvious that the amount of RC beam is larger than all the other alternatives, which even shows a 10x difference in CO_2, CH_4 and NO_x. Meanwhile, except for the fact that the SO_2 emission of SC beam is a bit more than GLT beam, those of SC beam are smaller than that of GLT beam in other sectors.

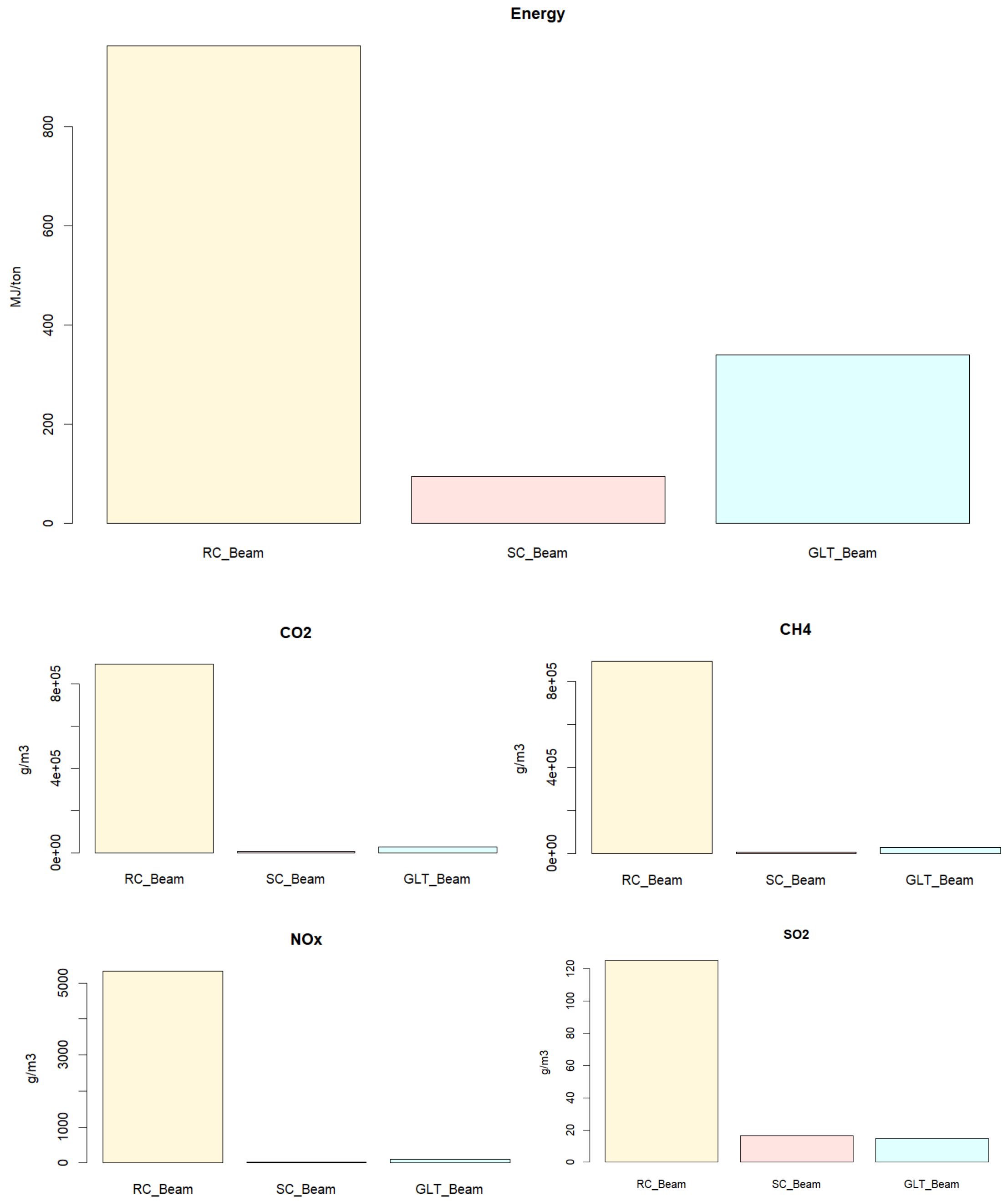

Figure 7 Energy consumption and chemical emissions for design alternatives

From plots above, we could observe that the most huge difference between RC beams and others lies in the scopes of CO_2, CH_4 an NO_x emissions, which could be a study target to research the cause within the fact in order to improve the production or maintenance measurements. On the other hand, there is a phenomenon of divergence between the reality that RC-built structure is more popular in some areas or building types, and the fact that the amount of RC beam in every sector is much larger than others.

Interestingly, other research[27] also shows that RC-built residential building could be more cost-efficient or affordable than that of timber structure. Within the results of another study[28] in China that compares the environmental impacts of different structural systems even presents a similar values in energy consumption(Primary Energy) and CO2 emissions(GWP).
These examples actually reflect to what I mentioned in the chapter 1.4 (Challenge & Limitations) that the LCI data or weights of materials could be different due to regional differences and thus influence the assessment results.

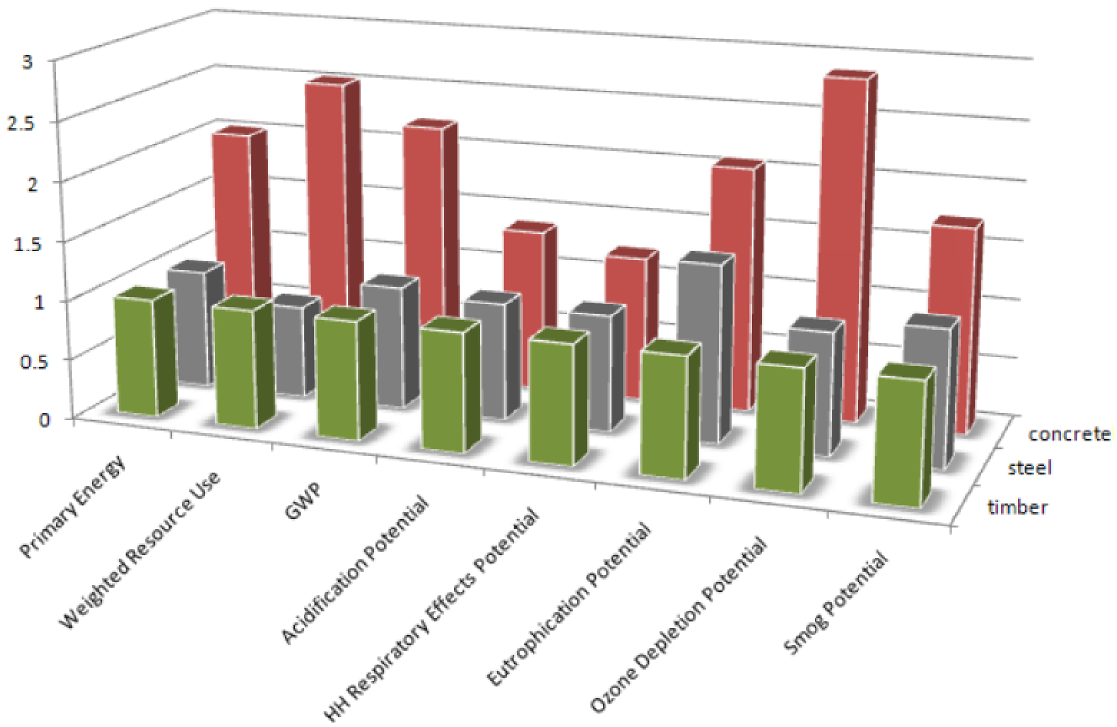

Figure 8 Diagram of normalized data[28]

4.3 MCDA-Analytic hierarchy process(AHP)

The objective of the study is to compare and rank different design alternatives by their energy consumption and chemical emissions. Within the process, one of the most crucial step is to define their corresponding weights by utilizing the pairwise comparison method between the chosen criteria, with Satty's 1-9 scale and the results of Figure 7 as references. Due to the fact that, our major target is the greenhouse gas, including CO_2 and CH_4, the weights between them and other pollutants(NO_x + SO_2) are about 5:1.

Meanwhile, because the effect and composition of energy consumption is complicated and hard to define, for example, it could both reflect to the financial cost or other pollutions depends on how it generates, I separate it as a unique branch different from other 2 major sectors like greenhouse gas and other air pollutants. Based on these aforementioned information, the final proportion between them is 5:1:1 (greenhouse gas : other air pollutants : energy).

To determine the actual weights of every criteria, I look back previous research[29], which shows that the thermal absorption of CH_4 is 28 times higher than the CO_2 with in a 100-year period. But since the gap between scales shouldn't be too large (neither greenhouse gas and other pollutants nor CO_2 and CH_4), the final weights between CO_2 and CH_4 is about 1:3.

Besides, other source[30] also indicates that although NO_x also presents a general downward trend as SO_2, its reduction is still less substantial than that of SO_2. Furthermore, a briefing[31] of U.S. government also presents that the impact of NO_x is much broader than that of SO_2. Therefore, I believe that a higher weight should be assigned to NO_x compared to SO_2, which is about 2:1.

Effects of Nitrogen Oxides (NOx)	Effects of Sulfur Oxides (SO2)
• Death and serious respiratory illness • Acidfies water, reducing biodiversity • Damages forests and their ecosystems thorough various way • Coastal eutrophication • Decreased visibility(regional hazard) • Speeds weathering of buildings	• Death and serious respiratory illness • Acidfies water, reducing biodiversity • Damages forests thorough various way • Decreased visibility(regional hazard) • Speeds weathering of buildings

Table 10 Effect of NOx and SO2[31]

The analysis result(Figure 9) shows that SC beam ranked top with the highest score of 53.6, followed by GLT beam with 38.7 and RC beam with 7.7. The top(GLT) scores 30% more than the second(SC), and almost 8 times than the lowest(RC). The overall results are aligned with my suspicions, while I didn't expect the score gap between SC beam and RC beam would be so huge, since the steel industry is well-known for high energy consumption and various chemical pollution.

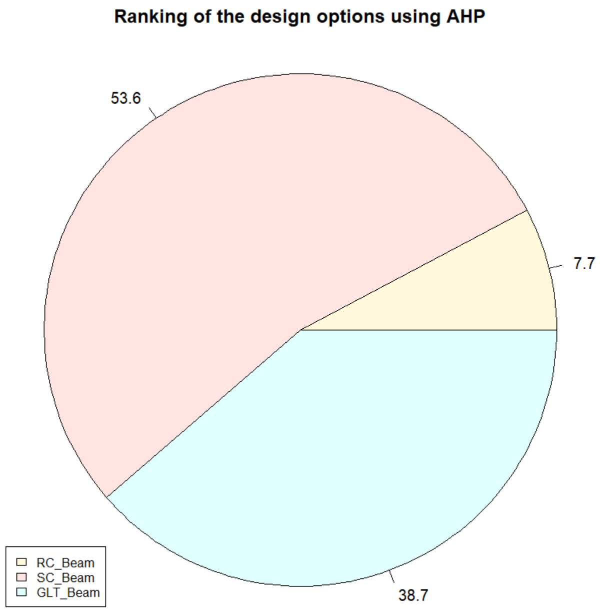

Figure 9 Analytic hierarchy process results

4.4 Engineering discussion toward analysis results

4.4.1 Reflections of analysis results

These analysis not only help us to understand the environmental impacts and engineering challenges within a highly-detail scope, including different life cycle stage and specific chemical pollutants, but somehow points out the directions of future improvement for material production or construction workflow. For example, passively, we could encourage manufacturers to focus on reducing the CO_2, CH_4 and NO_x output of RC structure since there are more than 10x gap between it and others. Actively, we could mix different types of structures to lower the output of specific chemicals or arrange plans to manage the potential costs and risk within each of life cycle stage.

4.4.2 Hypothesis scenarios

In construction projects, engineers and other stakeholders need to create their own high-performance criteria in order to find the most suitable solution for themselves.

Although the context could be different from this study, it still present the potential and enormous trad-off we would face between the environmental impacts and monetary cost as we could see by comparing Table 9 and Figure 9. To discuss the analysis results under real-world application, I propose 2 common scenarios which could use those analysis as reference for decision making of structure system:

- Scenario 1: 2-story single residential building in North America

  Challenges:

  1. High energy consumption due to cold winter

  Assumptions:

  1. To lower the environmental impact is prioritized than the monetary cost
  2. Sufficient budget

  Although the fact that RC buildings have higher performance in energy consumption in the operation phase, there are still methods including sealing the connection area or installing a high performance M&E equipment, especially the budget is rather flexible. Meanwhile, the difference of external pollution between these choices just can't be ignored as we can see in Figure 7 and the AHP result in Figure 9. For this specific scenario, timber structure would be the first choice, followed by the steel structure. Additionally, what could extend after the study is to compare the recycle rate and income of these 2 materials, since a higher price of steel could be expected than that of timber.

- Scenario 2: 4-story single residential building in East Asia

  Challenges:

  1. East Asia usually face natural disasters including earthquake or typhoon.
  2. Limited budget

  Assumptions:

  1. Financial cost would be prioritized than others, followed by the environmental impacts
  2. In most of the time, the structure only damaged partially than collapse.

  Within such context and based on our analysis results, timber-built structure would be the best choice, not only the total cost is lower but it's also more eco-friendly than the other. However, in some countries that don't have sufficient wood resource and rely on imported material, for example, Taiwan ,the cost of timber could be higher than that of concrete, meaning that the RC could be better than the GLT.

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