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CARBON MITIGATION STRATEGY WITH ENGINEERED TIMBER: THE CASE OF MJØSTÅRNET

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Abstract: *Mjøstårnet is a building that applies sustainable construction principles throughout its lifecycle, with timber as the primary building material. The use of timber, particularly locally-sourced and prefabricated timber, contributes to improved environmental performance by reducing transportation-related emissions, minimizing construction waste, and offering carbon storage potential during its service life. This research aims to explore opportunities to further reduce embodied carbon in the building by proposing alternative material scenarios. The study employs an embodied carbon assessment focusing on slab construction, which represents one of the largest contributors to upfront embodied carbon in the building. Alternative scenarios include replacing slab materials with cross-laminated timber (CLT) and fly ash concrete with varying substitution levels. The results indicate that replacing conventional slab materials with CLT can reduce embodied carbon by 25.59%, while the use of fly ash concrete with a 40% replacement level achieves a reduction of 14.07%. The combined application of these strategies demonstrates a potential embodied carbon reduction ranging from 29.47% to 39.81%. These findings confirm that material substitution, particularly in slab construction, is an effective strategy for mitigating embodied carbon in sustainable building design.*
Keyword: *Embodied Carbon, Timber Construction, Sustainable Construction Technology*

Abstrak: Mjøstårnet merupakan bangunan yang menerapkan prinsip konstruksi berkelanjutan selama umur bangunan, dengan kayu sebagai material utama. Penggunaan kayu, khususnya kayu lokal dan prefabrikasi, berkontribusi pada pengurangan emisi karbon melalui potensi penyimpanan karbon, efisiensi transportasi, penghematan energi, serta minimisasi limbah konstruksi. Penelitian ini bertujuan untuk mengevaluasi peluang peningkatan kinerja keberlanjutan bangunan melalui pengurangan embodied carbon, dengan fokus pada elemen struktur yang memiliki kontribusi karbon terbesar, yaitu plat lantai. Metode penelitian dilakukan melalui perhitungan *embodied carbon* pada beberapa skenario alternatif material, meliputi penggantian pelat lantai dengan *cross-laminated timber* (CLT) dan beton *fly ash* dengan variasi kandungan. Hasil penelitian menunjukkan bahwa penggunaan CLT mampu menurunkan embodied carbon sebesar 25,59%, sementara penggunaan beton fly ash dengan kandungan 40% menghasilkan penurunan sebesar 14,07%. Kombinasi kedua strategi tersebut berpotensi mereduksi *embodied carbon* antara 29,47% hingga 39,81%. Temuan ini menegaskan efektivitas pemilihan material sebagai strategi mitigasi *embodied carbon* pada bangunan berkelanjutan.
Kata Kunci: Emisi Karbon, Konstruksi Kayu, Teknologi Konstruksi Kayu

INTRODUCTION

Environmental degradation is an increasingly critical global challenge, with climate change, pollution and depletion of natural resources posing a serious threat to the survival of life on earth. One significant cause of environmental degradation is human activity, including the building construction sector. Building construction alone accounts for 39% of the total carbon emissions on earth (Figure 1) (Green Building World Council, 2017). Large-scale building construction and the use of conventional materials such as concrete and steel have contributed to increased carbon emissions, land degradation and consumptive energy use.

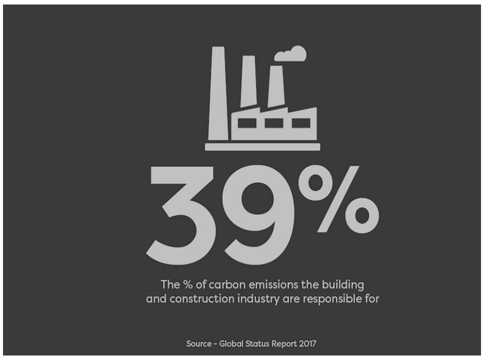

Figure 1. The construction sector is responsible for 39% of carbon emissions
Source : Global Status Report, 2017

To overcome this problem, the concept of sustainable construction is being widely applied in industrial sectors. Sustainable construction, according to Jackson (2021), involves utilizing renewable materials in buildings to minimize their environmental impact, reduce energy consumption, and minimize construction waste. In recent decades, the main focus of sustainable design application has been on energy efficiency, in which buildings are designed to reduce their operational carbon (Pomponi et al., 2020). However, aligned with the net-zero targets, the significance of embodied carbon, that is resulted from material production, transportation, construction processes, and end-of-life material disposal, has increased, making efforts to reduce embodied carbon become more crucial (Julistiono et al., 2024).

There are several principles that can be applied to achieve sustainable construction and reduce carbon emissions. The earlier the strategy is implemented, the larger the embodied carbon reduction potential that can be achieved, as highlighted in “build nothing, build less, build clever, and build efficiently” principles (WGBC, 2019).

- Planning phase
  The strategy applied in this planning phase has the main objective of reducing the need for new building construction. This approach is based on the idea that new construction often requires significant resources, in the form of energy, materials, and land. It is therefore necessary to reorganize and reuse existing buildings for new functions rather than demolish them and build new ones.
- Design phase
  Strategies in this phase focus on optimising material use by considering the entire life cycle of the building, from construction to the end of its life. Here, reducing embodied carbon often includes two building elements – materials and structures.
  - Materials
    In terms of material use, the main strategy is using materials that require less carbon emissions to produce, assemble/construct, maintain, and demolish at the end of their life.
  - Structures
    In terms of building structures, the main strategy is designing an efficient structure, which has a less weight, but good structural load capacity.
- Construction phase
  In an effort to achieve more sustainable construction, it is important to choose methods that minimize construction waste and reduce the negative impact on the environment. Low-carbon construction methods, such as the use of prefabricated elements and off-site construction are recommended to achieve efficiency in construction labour, time, and cost. In addition, using local materials can help reduce carbon emissions during transportation.

According to Pomponi et al (2020), of the several principles that can be applied, one of the most effective principles for reducing embodied carbon emissions is to use materials that have carbon-absorbing properties such as wood. In the past, wood was considered inappropriate to be used as the main material for building construction, especially for larger buildings, because wood has limitations in strength, a high risk of fire, and is vulnerable to weather and pests (source). Advancements in technology have led to the development of engineered wood products such as Glue-Laminated Timber (glulam) and Cross-Laminated Timber (CLT), which offer improved strength and performance of timber construction (Lestari, 2017).

Glulam has several advantages over ordinary wood (Abdullah et al., 2020; Ramage et al., 2017). Glulam has greater strength and rigidity making it possible to create wider spans. In addition, glulam is also durable because it is resistant to weather and chemicals and has high resistance to fire. There are also several advantages of CLT (Lestari,2017; Parajuli et al., 2018), CLT is a renewable material that can match the strength standards of concrete and bricks. In addition, CLT is a material that is easy to maintain and easy to install.

Wood is a material that has carbon sequestration potential and can store carbon, hence buildings made of wood will store carbon throughout their life, or act as carbon sinks (Figure 2) (Churkina et al, 2020; Yupa et al, 2024). In addition, wood is also a recyclable material, so that when the building is no longer functioning or is demolished, wood components can be disassembled and then reused or recycled, so that the carbon is still stored as long as the wood is not incinerated.

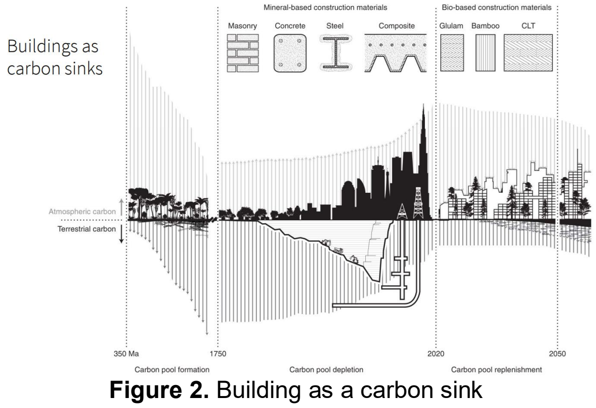

Figure 2. Building as a carbon sink
Source : Churkina et al., 2020

This article presents the implementation of sustainable construction principles on a building case study that was constructed with engineered timber as the main construction. Mjøstårnet, currently the tallest timber building, was chosen as the case study to analyze. After analysing the carbon reduction strategies applied in the project, alternative scenarios were proposed to look at the potential to reduce further the carbon emissions, and embodied carbon calculation were performed to quantitatively assess the scenarios proposed.

METHODOLOGY

A mix of qualitative and quantitative research methods was implemented in conducting this research. Several stages were performed in this research, including conducting literature studies, analyzing case studies, proposing alternative scenarios to further reduce carbon emissions, and quantitative embodied carbon assessment.

1. **Literature Study**
   Literature study is conducted to understand the importance of sustainable construction, the strategies to reduce carbon emissions, and the characteristics of engineered timber, which were used to select and analyze the case study. Existing literature was also studied to develop improvement plans and to calculate the embodied carbon.
2. **Case Study Analysis**
   To study the implementation of sustainable construction principles in real-life buildings, a case study was selected. Since the research focuses on the potential of wood, the use of engineered timber such as glulam or CLT has become the main criterion in selecting the case study. Mjøstårnet is the selected case study, documentary research was carried out to collect all project data. Then, the case study was analyzed against the principles of sustainable construction, to identify the carbon reduction strategies implemented in the building.
3. **Alternative Scenarios**
   After analyzing the case study and finding the sustainable construction principles that were applied, alternative scenarios were proposed to study the potential of further improving the building performance in terms of its carbon emissions. Here, low-carbon material alternatives were observed and applied to replace some building parts to reduce total carbon emissions in constructing the building.
4. **Embodied Carbon Assessment**
   This phase was conducted to provide a quantitative assessment of the effectiveness of the alternative scenarios proposed. Here, the embodied carbon reduction resulted by each alternative scenario was identified. The higher the percentage of the carbon reduction signifies the effectiveness of the scenario proposed.
   The embodied carbon assessment was carried out based on ISO 14040 (ISO, 2016) regarding Life Cycle Assessment (LCA) framework. The goal was to calculate the embodied carbon produced in the construction of the case study and its alternative scenarios, to look at the carbon reduction potential in each alternative scenario. The scope of the calculation includes upfront embodied carbon related to material production (A1-A3), which contributes to around 50% of the whole life carbon emissions (Gibbons et al., 2022). For inventory analysis, the embodied carbon factors (ECF_{A13}) were taken from Inventory of Carbon and Energy (ICE) Database (Craig & Hammond, 2019), since the case study is located in Europe. The calculation formula was obtained from the guide from the Institution of Structural Engineering (ISE) (Gibbons at al., 2022). Global Warming Potential (GWP) was utilized for the impact assessment, normalized with the total gross floor area (GFA) of the building. Therefore, the embodied carbon emissions are presented in kilograms CO_2 equivalent/m2.

CASE STUDY

The case study selected is Mjøstårnet, which is one of the tallest timber-constructed buildings in the world (Figure 3). Mjøstårnet is a building that has several functions such as offices, hotels, restaurants, and apartments. This 18-story building is located in Brumunddal, Norway, more precisely near Lake Mjøsa. The name Mjøstårnet itself comes from Norwegian which means "The Tower of Lake Mjøsa" (Pintos, 2020).

Mjøstårnet first emerged from the thoughts of a Norwegian investor named Arthur Buchardt, who often invested in hotel projects. Growing up in the Brumunddal area, he wanted to create a new innovation where he could show everyone his success in creating a building that used local materials from local suppliers and local labor. He also has a clear vision for Mjøstårnet to become a symbol of sustainable construction.

Figure 3. Mjøstårnet
Source : ArchDaily, 2020

Mjøstårnet was designed by a team of architects called Voll Arkitekter and assisted by contractor Hent AS. With an area of 15,000 m^2, Mjøstårnet first started its construction process in April 2017. After four years of construction, Mjøstårnet was completed in March 2019. Mjøstårnet's design concept is sustainable, as almost all of the materials used are timber. Mjøstårnet was also designed by Voll Arkitekter with the surrounding environment in mind so that the building does not damage the existing environmental setting but rather creates a harmonious relationship between the building and the landscape.

The materials used in this building are dominated by pine and fir wood. According to Liven & Abrahamsen (2023), the main load-bearing members, such as columns, beams, and bracin, were constructed with glulam from pine trees. In addition to the main load-bearing members, glulam is also used for the floors, pergolas, and facades. For Level 2 to 11, the floors were made of glulam and Laminated Veneer Lumber (Figure 4). For the pergola, the installation was quite different. Being on the highest floor of the building, the pergola was expected to be exposed to various kinds of weather. To reduce the possibility of shrinkage, four glulam members were connected at each end to form a cavity in the center. In addition to glulam, CLT is also used in this building, particularly in the walls for the elevator and escalator. However, these walls do not serve as lateral stability elements of the building. CLT is also used as the material for the balconies of this building.

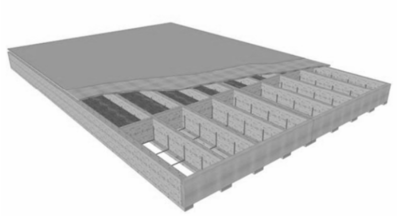

Figure 4. Glulam & LVL as floor material
Source : Abrahamsen, 2017

While the slabs of Level 2 to 11 use glulam, slabs of Level 12 to 18 use concrete slabs (Figure 5). This is because Level 12 to 18 function as apartments, hence users' comfort must be considered more. By employing concrete slabs rather than timber, acoustic comfort for apartment residents can be maintained properly. According to Liven & Abrahamsen (2023), this has caused Level 12 to 18 to have larger structural weight, compared to Level 2 to 11.

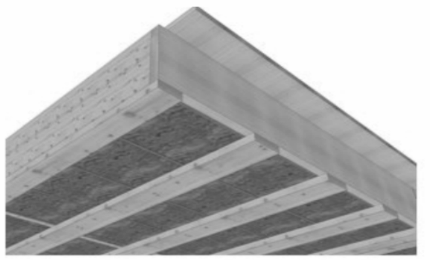

Figure 5. Timber & concrete as floor material
Source : Abrahamsen, 2017

The structural system used by Mjøstårnet is a column-beam frame structure that is responsible for resisting vertical loads and bracings that resists lateral loads (Figure 6). These two structural systems work together to maintain the stability of the building under all load conditions.

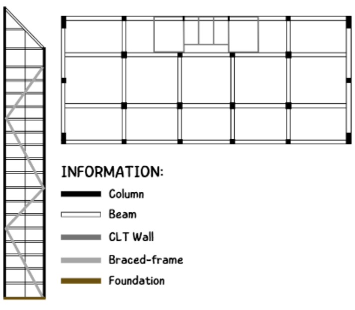

Figure 6. Layout of structural elements

The vertical load distribution system starts with the loads received by roof trusses or floor slabs which are then transferred to the beams. Columns receive the loads transferred by the beams and then transfer them to the foundation. As for the lateral load distribution system, loads are first received by the building facade which are then transferred to the floor diaphragms. The diaphragms transfer the loads to the braced-frames as the lateral supporting elements (Figure 7).

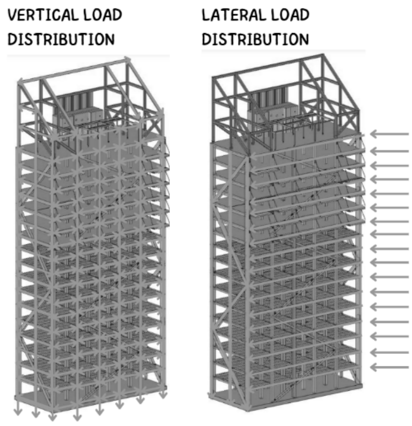

Figure 7. Building load distribution

RESULT AND DISCUSSION

1. Application of Sustainable Construction Strategies

After analyzing the Mjøstårnet, it was found that the building has applied several sustainable construction principles, including:

- **Using natural and local materials**
  The main material used by Mjøstårnet is timber from spruce and pine trees obtained from local forests around the building (Figure 8). Using natural material such as timber can reduce upfront embodied carbon. Additionally, by using local materials, the carbon emissions from material transportation can be reduced.

Figure 8. Forest where the materials were taken
Source : ArchDaily, 2020

- **Carbon sequestration potential**
  Timber is one of the materials that can store carbon during its use (Pomponi et al, 2020). Therefore, as long as timber components are used in this building is still in use, the carbon will be trapped in the timber
- **Utilizing offsite construction**
  Engineered timber components used in the building are prefabricated and assembled at the factory, to minimize onsite construction (Abrahamsen, 2017). The glulam wood used come from Moelven Limtre, which is 20 km from the site by road, while the CLT components were sourced from Stora Enso, 45 km away by road (Figure 9). Using glulam and CLT components

means the building was constructed with offsite construction/prefabricated materials, hence, the construction components can be used immediately upon arrival at the site to achieve efficiency in construction time and labor.

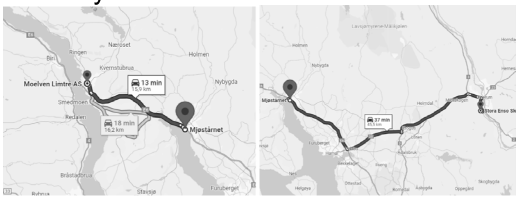

Figure 9. Factory distance to site
Source : Google Maps, 2024

- **Minimizing construction impact**
  Timber construction is commonly lightweight, thus it does not require deep foundations, unlike concrete and steel construction, which require strong and deep foundations. Because deep foundations are not needed, the environmental impact of the construction on the balance of the natural environment around the building can be minimized.
- **Structural efficiency**
  Although timber construction is known to be lightweight, it has great load-carrying capacity/strength. Therefore, by employing timber structure that tends to be lighter than concrete , structural efficiency can be achieved and the use of material can be reduced.

2. Alternative Scenarios

By using engineered timber, the case study has been found to implement several sustainable construction strategies. Alternative scenarios were then proposed with the main objective of finding out whether it is possible to improve the building performance and reduce further the embodied carbon resulting in the building construction. While the embodied carbon emissions include carbon emissions generated during the entire construction process, including the material production, transportation, installation, repair and maintenance, and building end-of-life (BRE, 2016), alternative scenarios focus on replacing materials that have less embodied carbon than existing materials (A1-A3).

According to research conducted by Thornton Tomasetti in 2019, the part of the building that has the highest embodied carbon is the floor with 47% in commercial buildings, 40% in educational buildings and 42% in domestic buildings (Figure 10).

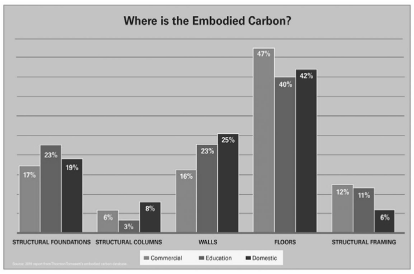

Figure 10. Embodied carbon in building elements
Source : Tomasetti, 2019

As Mjøstårnet is a commercial building as well as a domestic one, the most embodied carbon in this building is on the floors. Therefore, the alternative scenario proposed is to replace the slab materials with lower carbon options.

The existing materials used on the slabs of this building are timber and concrete (Figure 11). Hence, the alternative scenarios proposed consist of changing the specification of the timber and concrete used in the building slabs with lower carbon alternatives.

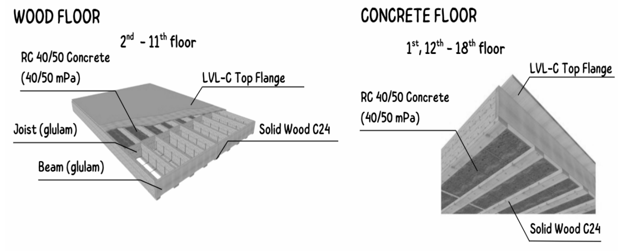

Figure 11. Floor material
Source : Abrahamsen, 2017

2.1. Using CLT for the building slabs

Changing the timber slab construction into CLT floors may reduce further the embodied carbon and produce a simpler floor structure (Figure 12). Advantages of CLT become the main considerations in its selection as the alternative floor structure proposed, such as having structural properties and strength that can match concrete, can be used in tall buildings, can be prefabricated before being installed on site so that it saves labor and time, and minimizes construction waste and disruption during the construction process (Lestari, 2017).

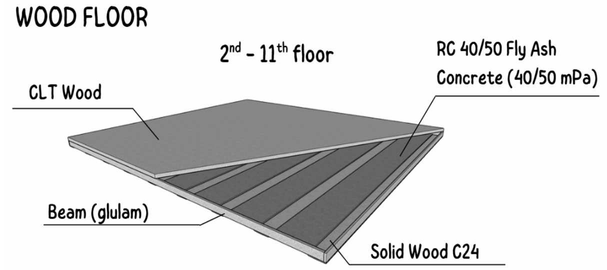

Figure 12. Timber floor structure

For high-rise buildings such as Mjøstårnet, there are fire resistance regulations that need to be adhered to. The main structure of the building must withstand 120 minutes of fire, and secondary load-bearing members such as floors must withstand 90 minutes of fire (Abrahamsen, 2017). Therefore, the dimension of the CLT slabs were selected based on the XLAM Fire Design Guide standard (Figure 13). Since the Mjøstårnet has a span of 7.6m, CL7/270 was selected as the size of the CLT slabs.

Australian Protected Span Table FRL 90/90/90 (maximum span in metres)
Time for interface to reach 300° > 30mins

Panel Designation	Q = 2.0 kPa			Q = 3.0 kPa			Q = 5.0 kPa		
	SDL			SDL			SDL		
	0.5 kPa	1.0 kPa	2.0 kPa	0.5 kPa	1.0 kPa	2.0 kPa	0.5 kPa	1.0 kPa	2.0 kPa
7 Layer Panels									
CL7/240	7.50	7.00	6.30	7.10	6.70	6.10	6.50	6.20	5.70
CL7/260	8.00	7.70	7.00	7.70	7.40	6.80	7.20	6.90	6.40
CL7/270	8.20	7.80	7.20	7.90	7.60	6.90	7.40	7.10	6.50
CL7/290	8.50	8.10	7.60	8.20	7.90	7.40	7.70	7.50	7.00
CL7/310	8.70	8.40	7.80	8.40	8.10	7.60	7.90	7.70	7.20

Figure 13. Australia Protected CLT Span Table
Source : XLAM, 2023

2.2. Using fly ash concrete

In terms of the concrete slabs, the alternative scenario proposed is to change the conventional reinforced concrete used with concrete mixture with lower embodied carbon, i.e. fly ash concrete (Figure 14). Fly ash concrete has a smaller embodied carbon compared to ordinary concrete. There are several advantages of fly ash concrete: fly ash comes from the combustion of fine coal, so that a) it can reduce construction waste, b) it can increase the strength and durability of concrete, and c) it can reduce the use of water during the production process (Setiawati, 2018).

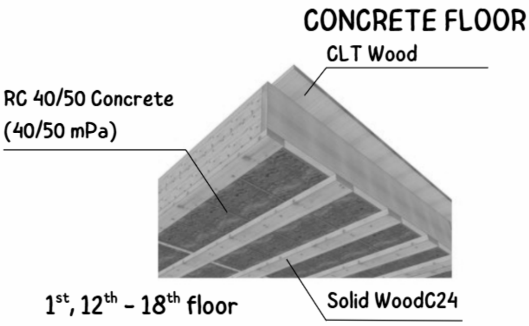

Figure 14. Concrete floor structure

3. Embodied Carbon Assessment

Embodied carbon assessment was performed to quantitatively assess the effectiveness of the alternative scenarios or the replacement of floor materials in reducing further the embodied carbon. Here, the embodied carbon resulting in constructing the buildings slabs with the existing materials was calculated, and then compared with the embodied carbon results if the alternative scenarios were employed instead of the existing materials. Calculation results show that the upfront embodied carbon resulting from the case study's existing slabs is 202.5 $kgCO_2eq/m^2$ (Table 1).

Three different calculations were carried out to calculate the potential embodied carbon reduction if the alternative scenarios were implemented: 1) changing the timber material into CLT,. 2) replacing the concrete material with fly ash concrete mixture, 3) combining the two.

For the first alternative scenario – using CLT to replace the timber slabs, calculation results show that by using CLT, the embodied carbon of the slab construction becomes 150.69 $kgCO_2eq/m^2$, causing embodied carbon reduction as much as 25.59% (Table 2).

For the second alternative scenario – using fly ash concrete, three different types of fly ash percentages were calculated (15%, 30%, and 40% of fly ash contents). The lowest embodied carbon can be obtained when using concrete with 40% fly ash content, in which the embodied carbon of the construction becomes 174 $kgCO_2eq$ /m^2,equal to 14.07% embodied carbon reduction (Table 3).

The last calculation was performed to simulate the maximum embodied carbon reduction by applying together CLT slabs and fly ash concrete slabs as the slab materials. Results show that if both scenarios were applied together,the embodied carbon of the slab construction would range between 142.82 and 121.88 $kgCO_2eq$ /m^2 for 15-40% fly ash content, equal to 29.47-39.81% embodied carbon reduction potential (Table 4).

Tabel 1. Existing embodied carbon

Building Part	Material	Quantity m³	Quantity kg	ECF_{A13}	Unit	(A1-A3) ($kgCO_2eq$)
Floor	RC 40/50 Concrete (40/50 mPA)	3,341.04	8,018,491.2	0.172	$kgCO_2e/kg$	1,379,180.49
	Glulam	2,951.45	1,770,870	0.512	$kgCO_2e/kg$	906,685.44
	LVL	1,866.28	1,119,768	0.390	$kgCO_2e/kg$	436,709.52
	Solid Wood C24	437.92	262,752	0.263	$kgCO_2e/kg$	69,103.78
					TOTAL	2,791,679.22
					GFA (m^2)	13,786.05
					TOTAL/m^2	202.50

Table 2. Embodied carbon reduction of using CLT

Building Part	Material	Quantity m³	Quantity kg	ECF_{A13}	Unit	(A1-A3) ($kgCO_2eq$)
Floor	RC 40/50 Concrete (40/50 mPA)	3,341.04	8,018,491.2	0.172	$kgCO_2e/kg$	1,379,180.49
	Glulam	1,917.95	1,150,770	0.512	$kgCO_2e/kg$	589,194.24
	CLT	152.536	91,521.6	0.437	$kgCO_2e/kg$	39,994.94
	Solid Wood C24	437.92	262,752	0.263	$kgCO_2e/kg$	69,103.78
					TOTAL	2,077,473.44
					GFA (m^2)	13,786.05
					TOTAL/m^2	150.69
Reduction of Carbon Emissions				Total Reduction		51.81
				Percentage		25.59%

Table 3. Embodied carbon after changing to fly ash concrete

Building Part	Material	Quantity		ECF_{A13}			Unit	(A1-A3) ($kgCO_2eq$)		
		m^3	kg	15%	30%	40%		15%	30%	40%
Floor	RC 40/50 Flyash Concrete (40/50 mPA)	3,341.04	8,018,491.2	0.159	0.142	0.123	$kgCO_2e/kg$	1,274,940.10	1,138,625.75	986,274.42
	Glulam	2,951.45	1,770,870			0.512	$kgCO_2e/kg$	906,685.44	906,685.44	906,685.44
	LVL	1,866.28	1,119,768			0.390	$kgCO_2e/kg$	436,709.52	35,693.42	35,693.42
	Solid Wood C24	437.92	262,752			0.263	$kgCO_2e/kg$	69,103.78	69,103.78	69,103.78
							TOTAL	2,687,438.84	2,551,124.49	2,398,773.15
							GFA (m^2)	13,786.05	13,786.05	13,786.05
							TOTAL/m^2	194.94	185.05	174.00
Reduction of Carbon Emissions					Total Reduction			7.56	17.45	28.50
					Percentage			3.73%	8.62%	14.07%

Table 4. Embodied carbon after being replaced with CLT wood and fly ash concrete

Building Part	Material	Quantity		ECF_{A13}			Unit	(A1-A3) ($kgCO_2eq$)		
		m^3	kg	15%	30 %	40%		15%	30%	40%
Floor	RC 40/50 Flyash Concrete (40/50 mPA)	3,341.04	8,018,491.2	0.159	0.142	0.123	kgCO2e/kg	1,274,940.10	1,138,625.75	986,274.42
	Glulam	2,951.45	1,150,770		0.512		kgCO2e/kg	589,194.24	589,194.24	589,194.24
	LVL	1,866.28	91,521.6		0.39		kgCO2e/kg	35,693.42	35,693.42	35,693.42
	Solid Wood C24	437.92	262,752		0.263		kgCO2e/kg	69,103.78	69,103.78	69,103.78
							TOTAL	1,968,931.54	1,832,617.19	1,680,265.86
							GFA (m^2)	13,786.05	13,786.05	13,786.05
							TOTAL/m^2	142.82	132.93	121.88
Reduction of Carbon Emissions							Total Reduction	59.68	69.57	80.62
							Percentage	29.47%	34.35%	39.81%

CONCLUSION

Mjøstårnet is one of the buildings that applies the principles of sustainable construction in the construction process from the beginning to the usage period. Its main sustainable construction feature is the use of timber as the main material in the building. By using timber, the building becomes more environmentally-friendly and has carbon storage potential as long as the timber components are still in use. In addition, this building also uses local and prefabricated timber, so that it can reduce the carbon released during the transportation process, save time, cost, and energy, and reduce construction waste.

To look at the possibility to further improve the sustainability of the building in terms of the embodied carbon emissions, there are alternative scenarios proposed to reduce the upfront embodied carbon of the construction by replacing the materials. Since the largest embodied carbon in the building is commonly caused by the slab construction, the alternative scenarios proposed include replacing the slab materials with CLT and fly ash concrete. After the calculation, it was found that by using CLT to replace the timber slabs in the building, embodied carbon can be reduced by 25.59%. By replacing conventional concrete slabs with fly ash concrete, with the largest content (40%), 14.07% of embodied carbon reduction can be achieved. When combining these two material replacements, there is a potential to reduce embodied carbon between 29.47% and 39.81%. This confirms that both alternative scenarios (using CLT and fly ash concrete) were effective in reducing the amount of embodied carbon emissions in building construction.

This research has some limitations. The focus of this research is on embodied carbon mitigation, hence the alternative scenarios proposed are limited to the replacement of materials, specifically slab materials, since they have the highest amount of embodied carbon compared to other building elements. This approach potentially ignores the carbon contribution of other construction elements that may also be significant in the context of the overall building. In addition, the calculation method used in this research does not take into account the nature of timber as a material capable of storing carbon over its lifetime. As a result, the analysis results presented tend to under-represent the potential benefits of wood as a sustainable material.

Future research is expected to expand the focus of the analysis to all building elements that have high potential to contribute to embodied carbon. Moreover, a complete LCA should be applied to account for the carbon sequestration potential of timber over the lifetime of the building.

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