PEIKKO
WHITE PAPER

SUSTAINABLE FRAME
OPTIMIZING BUILDING'S LIFE CYCLE CARBON FOOTPRINT AND OPERATIONAL EMISSIONS

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1. Introduction

In 2020, 70% of the world's emissions came from cities. Globally, the construction industry creates 30% of all the waste, is responsible for 40% of our energy consumption, and consumes 50% of natural resources. The building industry is also responsible for creating more than 30% of global CO_2 emissions.

Future urbanization rapidly requires sustainable solutions to meet this challenge. With the increasing recognition of the building industry's responsibility in climate change mitigation, it has become crucial to explore strategies, innovations, and solutions that effectively reduce total emissions and encourage sustainable practices. For this reason, we in the building industry need to be innovative in creating economical yet ecological solutions.

All the phases of a building's lifecycle create emissions. During the design and construction phase, the main emissions source is embodied carbon in the materials used, whereas the operational phase is mainly about the carbon emissions created by heating and cooling. At the end of a building's lifecycle, the carbon emissions derive from the demolition.

The development, design, and construction phases are estimated to account for a total of 30% of a building's emissions. Furthermore, over its entire life cycle, a building's operational emissions have a huge impact on the environment and are estimated to account for up to 70% of the total emissions amount (*Figure 1*).

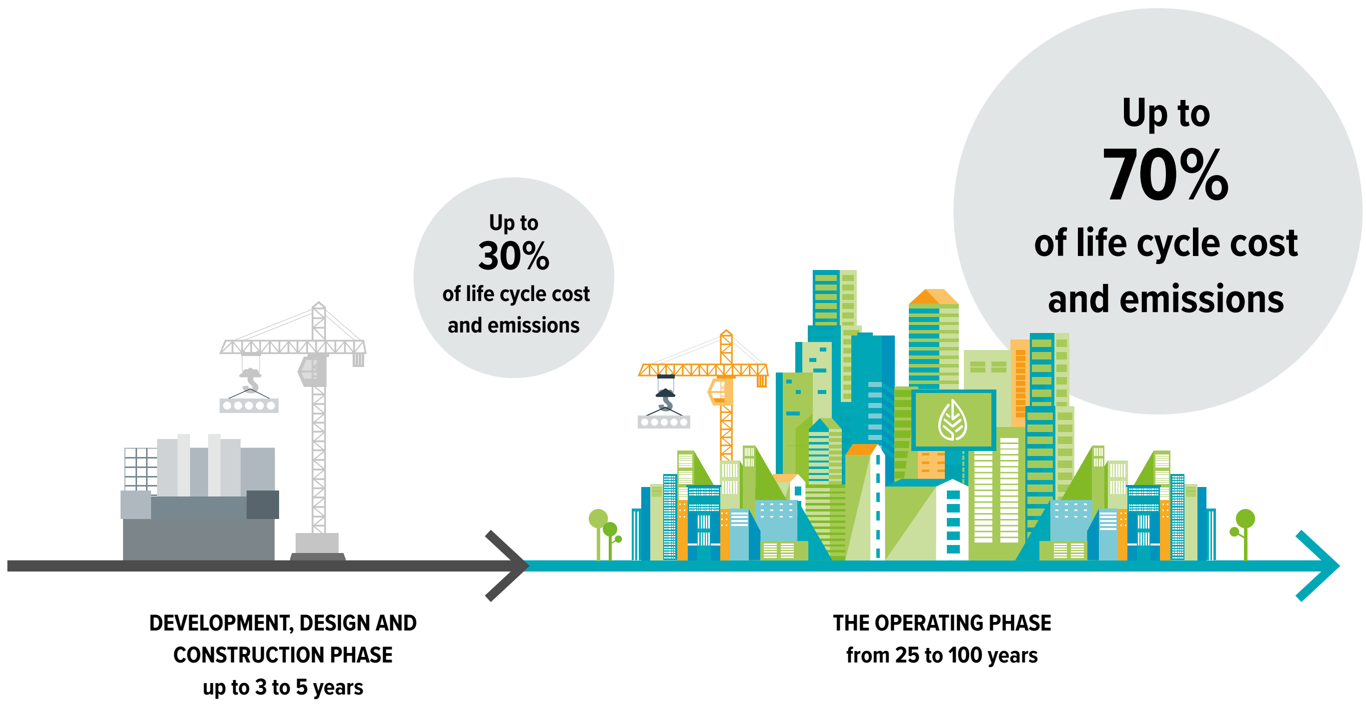


Figure 1. A building's economic and ecological footprints over its entire life cycle.

The most important decisions that lead to reduced emissions are made at the beginning of the design phase, so it is crucial that reliable data about the emissions of different products and solutions is available. Developing the efficiency of design tools and the data they provide on emissions is essential.

The right choice of materials made in the design phase of the construction process significantly impacts the emissions in the development, design, and construction phases as well as the operating phase. The materials are the main source of emissions in the construction phase, and by reducing, optimizing, and rethinking them the construction industry can significantly reduce emissions also in the operating phase.

The biggest impact on a building's operational carbon and lifecycle lies in a building's frame, as it accounts for approximately 25 – 30% of the building's total embodied CO_2 emissions. Of these emissions, the building's floors account for approximately 50% of the frame's emissions. The higher the building, the greater the environmental impact – as high-rise solutions are increasingly needed, the importance of the right frame solution is even more crucial.

Innovative frame design in the early stages greatly improves the sustainability of buildings in both the construction and the operational phases, as the design phase allows for emissions reduction by maximizing space utilization and optimizing building design. Minimizing the environmental impacts of a building frame requires a well-thought-out design with an end-of-life perspective considered; better cubic efficiency and more flexible space expand the building's lifespan. The optimized use of building materials with a preference for environmentally friendly materials is important; low-carbon building materials and biogenic building materials make an impact and reduce emissions. Simultaneously, the construction site should consider waste reduction and energy efficiency matters. The buildings should be designed and built for reuse, including design for disassembly and reuse of materials whenever possible.

One of the key focuses of this study is the conservation of materials in building frames. The concept of "all materials need to be saved" underlines the need to prioritize resource efficiency. Throughout the construction sector, the availability of all materials is limited, and the negative environmental impact of the construction industry has become topical. It is of utmost importance to reduce emissions by reducing and rethinking materials. The construction industry must pay attention to materials and emissions during both the construction phase and the operational life cycle of a building to understand the big picture.

Building "hybrid frame construction" – a combination of concrete, steel, and timber, refers to a technique that combines different materials in the construction of a building's frame. It involves using a combination of materials such as wood and steel along with concrete. This approach allows of each material to be utilized, resulting in an efficient and cost-effective building system than using single material alone. The hybrid frame construction method offers flexibility in design and performance, making it increasingly popular in modern construction projects. By combining materials it might enable to create new solutions whose requirements individual materials cannot meet both economically and ecologically.

Furthermore, by choosing products that are manufactured by using more recycled raw materials with lower CO_2 emissions in the process, even challenging environmental targets can be achieved. By using the waste hierarchy pyramid model, we can utilize the best method to save and optimize materials and further increase resource efficiency (*Figure 2*).

Figure 2. A Waste hierarchy model of how to reduce the resource consumption in the building frame.

Understanding the interrelation of different solutions and the emissions they create is essential for improvement. It is crucial already at the early stage of the project to compare and measure the carbon footprint and emissions of different solutions. These comparisons allow us to eventually choose the most sustainable solution for the entire lifespan of a building.

This paper explores the importance of optimizing a building's life cycle carbon footprint and operational emissions through the implementation of a frame system. The paper will address ways to reduce operational carbon in a building frame by evaluating the full building lifecycle and identifying opportunities for emissions reduction and optimization within the frame. The study focuses on three primary construction materials; concrete, steel, and timber, and examines how their environmental impact mitigates a building's total environmental footprint.

The study consists of a comprehensive analysis of different framing systems for a 10-story office building, focusing on the structural design aspects, heating energy evaluation, and sustainability impact to understand the effects of different frame solutions, particularly the thickness of the floor, on the sustainability of the building.

The study uses proven structural and lifecycle assessment techniques for optimizing the lifecycle carbon footprint and operational emissions, offering practical insights for the industry stakeholders. The paper presents detailed insights into the methodology used, the environmental impact of different framing systems, and combined results that offer a holistic view of their environmental performance over their entire lifecycle. The aim is to understand, in connection with a building frame, the role of operational carbon as a contributor to the overall carbon footprint. By presenting results, this research aims to contribute to the ongoing efforts in the building industry to address climate change, enhance sustainability, and foster a more responsible approach to construction. The aim of this paper is, by comparing different solutions, to identify the optimal solution for a sustainable frame that optimizes a building's life cycle embodied carbon footprint and operational emissions.

2. Structural design

2.1. Initial design

The task was to design a conceptual office building for sustainability comparison. The comparison will compare different frame systems.

The aim of the comparison is to study the effects of Peikko DELTABEAM® on overall sustainability of the building frame. The reference building was defined within the project to be of 10 floors in height, with roughly 1000 m^2 area per floor. The required free room height was set to 3200 mm and the structural grid was selected to be 7 × 7m for all solutions. The frame system is estimated with rough approximations and further optimizations are possible.

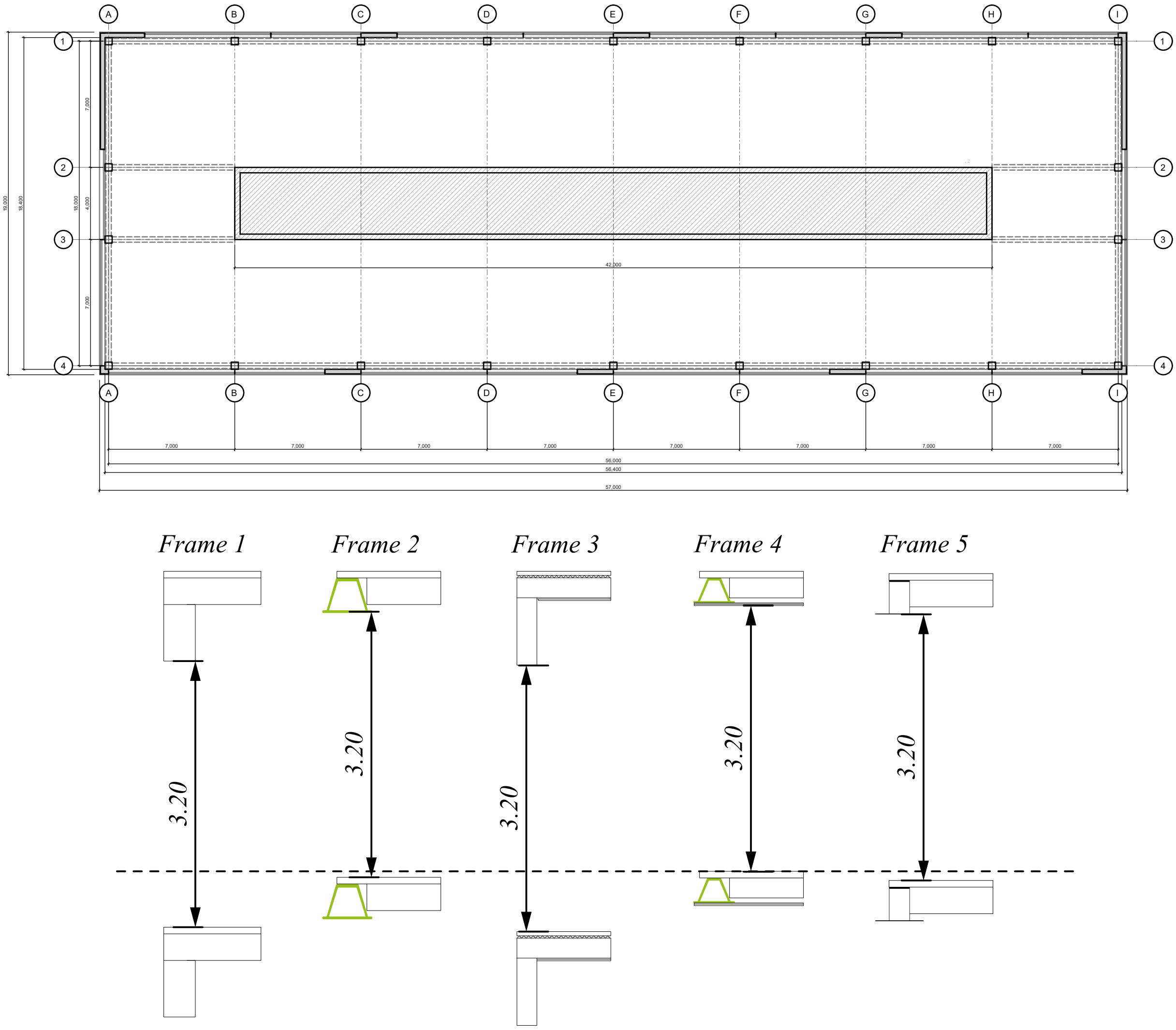


Figure 3. Schematic representation of free floor height between the frame options.

The following cases were studied (shown in figure below):

- **Frame 1**
  Reference frame from concrete elements (hollow-core, beams and columns)
  Floor height 4280 mm
- **Frame 2**
  Concrete element frame with DELTABEAM®
  Floor height 3680 mm
- **Frame 3**
  Timber element frame
  Floor height 4328 mm
- **Frame 4**
  Timber hybrid frame with DELTABEAM®
  Floor height 3608 mm
- **Frame 5**
  Concrete-steel hybrid frame with WQ-beams
  Floor height 3880 mm

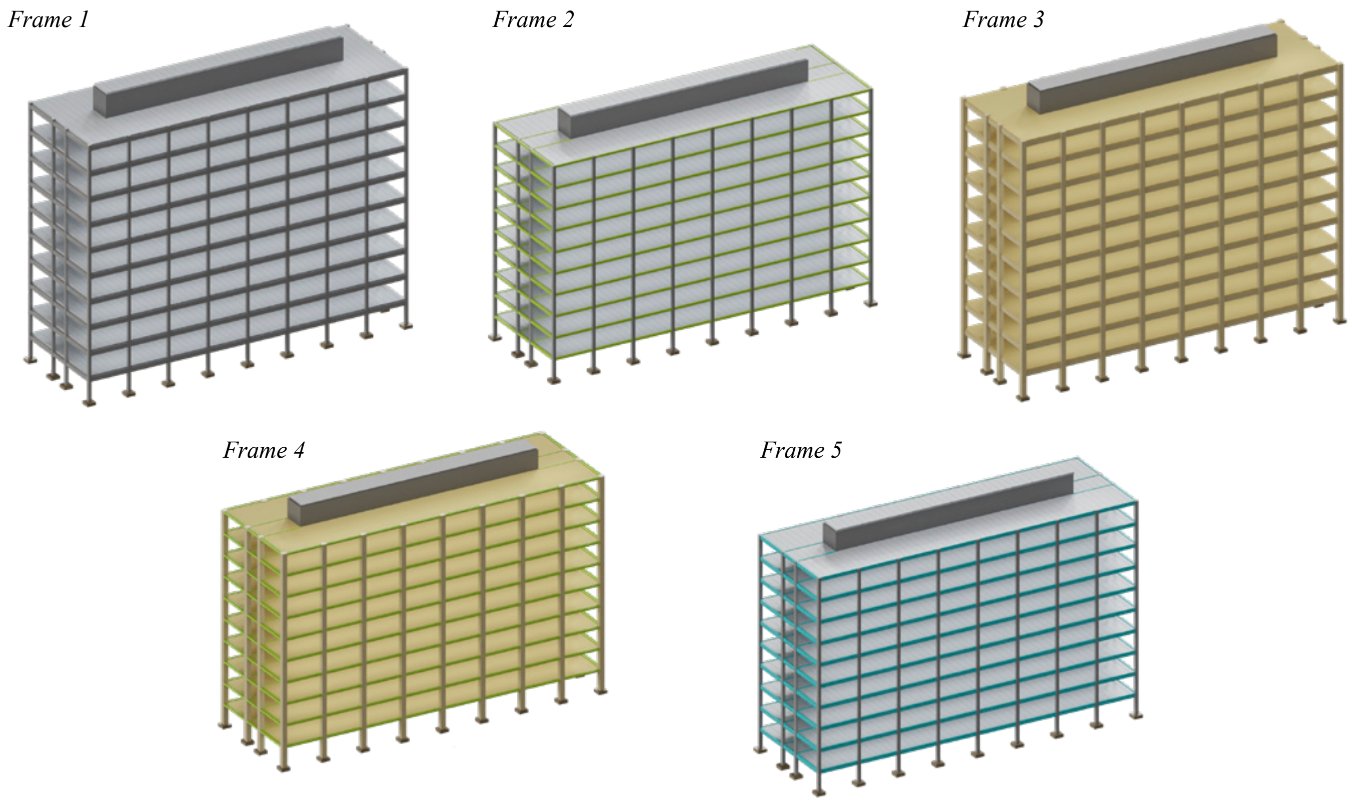


Figure 4. Representation of different frame types in the study. Notice, the pictures are for visualization purposes, actual calculation may differ from these models.

All the frame types were also studied with "green" building products:

- Green concrete/hollow-cores with -20% carbon reduction
- DELTABEAM® Green

2.2. Design principles and methodology

All the frame systems have a cast-in-situ concrete core in the middle, assumed to take care of the needed bracing for the frame. Slabs are designed and tied together for transferring horizontal forces. Roof level can be designed to brace the roof for horizontal loads, or it can have a separate horizontal bracing.

Floor vibration was checked with a preliminary design analysis. The check was conducted on timber-based floors according to the coming Eurocode 5 draft (because current Eurocode has no methods to assess resonant floors). The vibration behavior was checked together with the timber-beam frame with non-composite floor slab and with DELTABEAM® frame, with timber-concrete-composite slab. The overall vibrational performance was calibrated to perform at a typical level for building of this type.

Preliminary design system for carbon assessments was used for this study. The system is called "Fenix by Ramboll" and will be referred only as Fenix in this report. The system takes space objects as inputs, together with desired frame structures, materials and loads and produces a preliminary design calculation and representation of the frame, together with the data of embedded carbon emissions in LCA phases A1 – A3.

Stuctural analysis done with preliminary design methods according to Finnish codes:

- Consequence class
  - Offices CC3
    (YMA for load-bearing structures, SFS-EN 1990 + national annex)
- Consequence class for disaster loads CC2b
  (YMA for load-bearing structures, SFS-EN 1991-7 + national annex)
- Reliability class
  - Offices RC3 K_{fi} = 1.1
    (SFS-EN 1990 + national annex)
- Design service life
  - Foundation 100 a
  - Frame 50 a

LOADS

Office (Class B)
Live load q = 2.5 kN/m^2

Dead loads:

Screed:	g_{k1} = 1.0 kN/m^2
Floor slab:	g_{k2} = 1.0 kN/m^2
Installations:	g_{k3} = 0.3 kN/m^2
Finishings:	g_{k4} = 0.1 kN/m^2
Intermediate walls:	g_{k3} = 0.3 kN/m^2

Snow-loads

Nominal snow load	sk = 2.75 kN/m^2
Wind effect coefficient	Ce = 1.0
Temperature coefficient	Ct =1.0
Design snow load	s = 2.2 kN/m^2
Combination coefficients	$\psi 0$ = 0.7
	$\psi 1$ = 0.5
	$\psi 2$ = 0.2 *RIL201-1 table. A1.1*

Accident and crash loads

Accident and crash loads are not considered in this concept.

Construction loads

Loads that are present during erection phase are not considered in this concept.

Ground pressure

Ground pressure or groundwater induced uplift is not considered in this concept.

Suspended ceilings

Added load-assumption from the suspended ceilings has been considered in the calculations.

Roof structures

If no better assumption was available, roof structures have been assumed to have a total self-weight of 1 kN/m^2

Façade and exterior envelope

The exterior envelope has been assumed to be non-loadbearing (only supporting self-weight and wind loads). The exterior wall structure is assumed to weigh 0.7 kN/m^2.

2.3. Frame systems

The materials used in the framing system include concrete, steel, timber, and other materials depending on the frame type. It is important to note that the frame types are not supposed to be compared to each other in a competitive manner. Rather, they are being used to showcase different building technologies.

Frame	Columns	Beams	Slabs	Surface1	Surface2	Reinforcement
Concrete element Frame 1	Concrete	Concrete 380 × 680	Hollow-core 320	Concrete screed 80mm		Steel mesh
DELTABEAM® – concrete hollow-core Frame 2	Concrete	DELTABEAM® D37-400A	Hollow-core 320	Concrete screed 80mm		Steel mesh
Timber Frame 3	Timber	Timber 240 × 810	CLT240	Gypsum screed 50mm	Gypsum layers	
DELTABEAM® – Timber Frame 4	Timber	DELTABEAM® D32-300A	CLT240 + Timber-Concrete Composite	Concrete screed 80mm	Gypsum layers	Steel mesh
Steel – Concrete hollow-core combination Frame 5	Steel	WQ400	Hollow-core 320	Concrete screed 80mm		Steel mesh

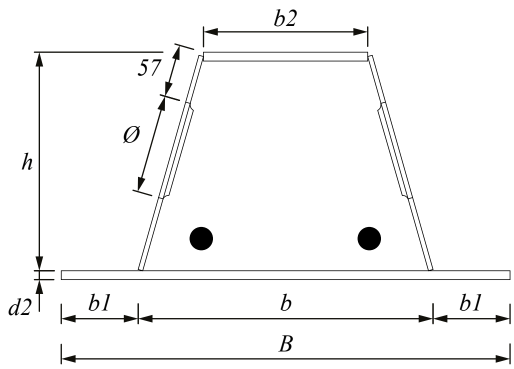
<u>Concrete element. Frame 1:</u>

- **Columns:** Concrete columns
- **Beams:** Concrete beams with dimensions of 380 × 680.
- **Slabs:** 320 mm Hollow-core slabs with an 80 mm thick concrete screed.
- **Reinforcement:** Steel mesh is used for reinforcement.

<u>DELTABEAM® – concrete hollow-core. Frame 2:</u>

- Columns: Concrete columns
- Beams: DELTABEAM® D37-400A or similar

Section	*b*	*h*	*d1*	*d2*	*b2*	*B*	*tw*
D37-400 A	0.4	0.370	0.02	0.010	0.180	0.660	0.005



- Slabs: 320 mm Hollow-core slabs with an 80 mm thick concrete screed.
- Reinforcement: Steel mesh is used for reinforcement.

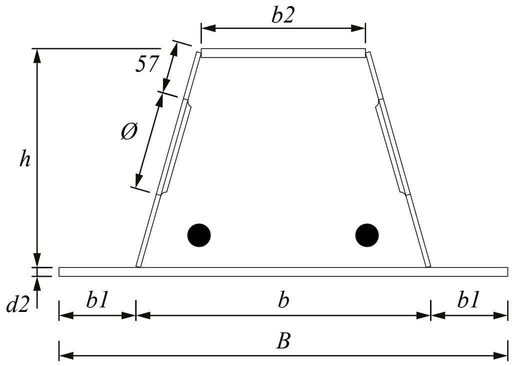
Timber. Frame 3 (concrete core):

- Columns: Glulam columns
- Beams: Glulam beams with dimensions of 240 × 810
- Slabs: CLT240 L7s2 slabs are used with floating gypsum screed applied with a thickness of 50 mm. Step-sound insulation is required.
- Surface: Gypsum layers are present on the bottom of the slab.

DELTABEAM® – Timber. Frame 4 (concrete core):

- Columns: Concrete columns
- Beams: DELTABEAM® D37-400A or similar

Section	*b*	*h*	*d1*	*d2*	*b2*	*B*	*tw*
D32-300 A	0.3	0.320	0.02	0.010	0.110	0.495	0.005



- Slabs: Timber-concrete composite slab with CLT240 L7s2 and 80 mm thick concrete top layer
- Surface: Gypsum layers are present on the bottom of the slab.
- Reinforcement: Steel mesh is used for reinforcement.

Steel – concrete hollow-core combination. Frame 5:

- Columns: Steel columns
- Beams: WQ400 beams (Assumed CO_2-coefficient 3.0kg CO_2e/kg)
- Slabs: 320 mm hollow-core slabs
- Surface: Concrete screed with an 80 mm thickness
- Reinforcement: Steel mesh is used for reinforcement.

Core structure in all options:

- Cast-in-place slabs generally h = 200 mm
- Concrete walls in the core b = 200 mm

2.4. Structural comparison and results

The results review the preliminary structural results according to the FENIX tool outputs. Fenix produced carbon footprints are only comparable within the selected frame systems in this setting. The results cannot be generalized in a broader perspective given the limitations of the carbon calculations. The actual CO_2 emission data is presented in the LCA part of this paper.

Table 1. Summary of structure heights. Additional layer thicknesses refer to floor screed/concrete layers and possible gypsum layers in the timber floors. Rank describes the ranking of the solution in relation to the floor structure thickness and total building height, no. 1 being the lowest solution.

Structure label	Slab thickness (mm)	Beam height (mm)	Additional layer thicknesses (mm)	Rank	Building total height (m)	Required floor-to- floor height (mm)
Concrete element. Frame 1	320	680	80	4th	42.8	4280
DELTABEAM® – Hollow-core. Frame 2	320	400	80	2nd	36.8	3680
Timber. Frame 3	240	810	78	5th	43.3	4328
DELTABEAM® – Timber. Frame 4	240	300	108	1st	36.1	3608
Steel – Hollow-core combination. Frame 5	320	410	80	3rd	36.9	3690

3. ENERGY DESIGN

3.1. Methodology

The methodology used to evaluate heating energy consumption for two different frame systems (taller vs. lower buildings) involves comparing two beam options for an office building and estimating differences in energy demand. The floor-to-floor height with a higher beam is 4.1 m and with a low profile beam the height is 3.4 m.

The differences in beam heights change the area of the facade and thus affect the heat losses. The calculation was completed using building energy and indoor climate calculation tool IDA ICE 4.8. The weather data for calculations is the FMI test weather for energy calculations (Helsinki TRY2020).

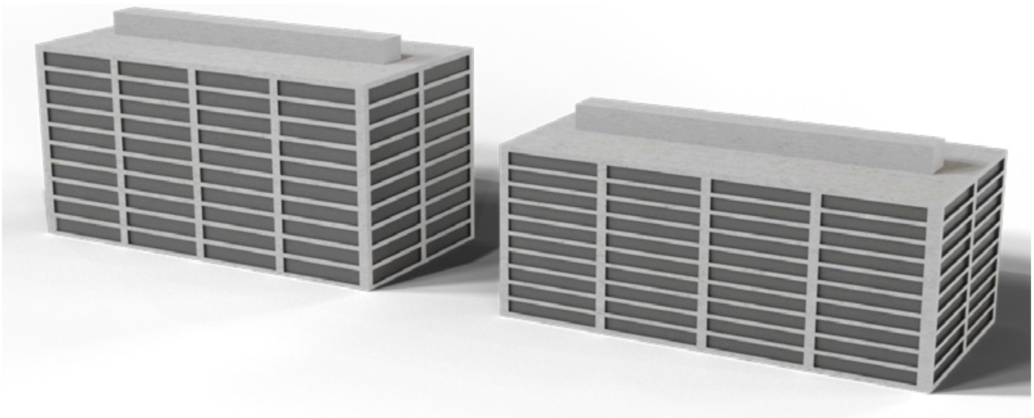


Figure 5. Compared building solutions side.

Supply air temperature:	+19 °C
Space heating setpoint:	+21 °C
Space cooling setpoint:	+25 °C

Occupants:	0.05 occ./m^2
Lighting:	7.0 W/m^2
User equipment:	12 W/m^2

Infiltration (q50):	1.0 m^3/h/m^2
Constructions:	Building code baseline: Ext. wall – 0,17 W/m^2K Roof – 0.09 W/m^2K Ground slab – 0.18 W/m^2K Windows – 1.0 W/m^2K
Airflow:	2.0 l/s,m^2

In tall beam option, window area is 37% of the whole façade. In low profile beam option window area is 42% of façade area. Only the area of external wall is changed. The heated net area of the building is 10,380 m^2. It is assumed that conduction through façade is similar behind the beam as in rest of the wall.

3.2. Results

Changes in the external area of the building cause changes in heating and cooling demand. Comparing the tall beam option to low profile option:

- The net area of the façade is **19%** higher with the tall beam option.
- Heat losses from façade are approximately **16%** higher.
- Zone heating demand is **8%** or 19 MWh higher with tall beams.
- Zone cooling demand is **7%** or 3 MWh higher with low profile beams.
  (The absolute difference in energy is relatively small)

The increased cooling demand is due to a combination of higher internal mass in occupied zones, higher air volume and increased overheat losses. With taller beams, during nighttime, more of the excess heat is lost from façade and the higher mass will keep the building cooler for longer.

	Tall beam	Low profile beam	Low b./Tall b.-%
Conductive heat losses in the façade	132 MWh	110 MWh	83%
Space heating energy demand	232 MWh	213 MWh	92%
Cooling energy for space cooling	40 MWh	43 MWh	107%

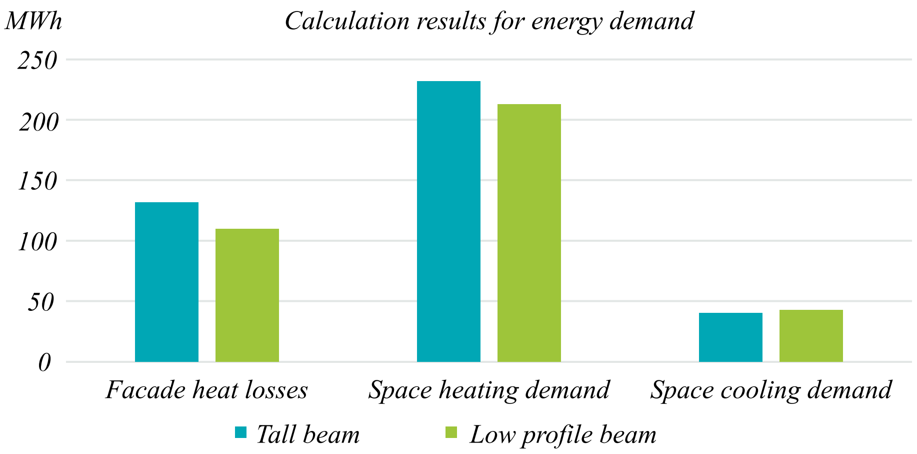


Figure 6. Results from the simulation.

4. LIFE CYCLE ASSESSMENT (LCA)

The Life Cycle Assessment (LCA) is a method used to measure the environmental impacts of a product or system over its entire life cycle. In this study, the LCA was applied to a 10-story office building, with the aim of calculating its carbon footprint using five different frame solutions.

4.1. Methodology

The Life Cycle Assessment (LCA) methodology used in this study was modified for the purpose of this study. It took into account various life cycle stages of the building, with an assessment period set at 50 years. The product stage (A1 – A3) was a critical component of the carbon footprint calculations, encompassing the emission impacts associated with manufacturing products and materials. The materials and quantities included in these calculations were based on Fenix calculations and structural designs.

The methodology employed in this study was based on the low-carbon assessment method for buildings published by the Finnish Ministry of Environment (version:2021). This method is grounded in the Level(s) method developed by the European Commission and various standards for sustainable construction such as EN 15643, EN 15978, EN 15804 and EN ISO 14067. The OneClickLCA tool was utilized in the calculation process, with an assessment period set at 50 years.

The life cycle stages considered in this assessment spanned from stages A to C, encapsulating the entire life cycle of the building. The product stage (A1 – A3) consisted of the emission impacts of manufacturing products and materials. The materials and quantities included in the calculation were derived from Fenix calculations and structural designs.

A1 – 3 Product stage	**A4 – 5** Construction stage	**B** Use stage		**C** End of life
A1 Raw material supply	**A4** Transport	**B1** Use	**B5** Refurbishment	**C1** Deconstruction
A2 Transport	**A5** Construction	**B2** Maintenance	**B6** Operational energy use	**C2** Transport
A3 Manufacturing		**B3** Repair	**B7** Operational water use	**C3** Waste processing
		B4 Replacement		**C4** Disposal

Figure 7. Building life cycle. Life cycle stages marked with green are included in the calculations.

A1 – 3 Product stage

In carbon footprint calculations, the product stage consists of the emission impacts of manufacturing products and materials. The materials and material quantities included in the calculation are based on Fenix calculations and the structural designs.

The emission data has been selected according to the calculation method and the following principles were applied:

1. Primarily, a product-specific EPD was used if material and manufacturer are known (DELTABEAM® or DELTABEAM® Green).
2. Secondarily, if exact product choices are not known, conservative GWP value in the National Construction Emissions Database (co2data.fi) was used.
3. In one case, a product-specific EPD was used even though manufacture was not known. This was done in case where a conservative value was not available (gypsum-based floor leveling screed).

A4 Transport

Transport distances were estimated separately by product using standard transport distances.

A5 Construction site operations

Site emissions are caused by energy use in construction site. Impacts of the construction site have been assessed according to the national emissions database which gives a standard value 78 kg CO_2e /m^2 for an office building. As part of the worksite operations, the surplus and waste of materials generated on site have been estimated as percentages of the amount of material according to the construction emissions database.

B4 Exchanges of construction products

Product replacements during the life cycle have been included in the review based on the estimated service life of the components. The service lives of the products have been estimated using the service life assumptions of the construction emissions database.

B6 Energy use

The energy consumption during the building's operating period has been estimated in accordance with the project's energy survey. Total heating and cooling energy needed were determined to highest and lowest building and other scenarios were interpolated based on that.

Emissions from energy production have been calculated in accordance with the construction emissions database. The emission factors for electricity and district heating are presented in *Table 2*.

Table 2. Energy source emission scenarios (Construction emissions database, 06/2023).

kg CO_2e/MWh	2020	2030	2040	2050	2060	2070	2080
Electricity	153	89	59	45	34	22	15
District heating	147	114	82	54	29	21	15

End of life C1 – C4

The impacts of demolition (C1) have been assessed using standard value for office building (14 kg CO_2e/m^2). Other end-of-life stages were estimated using material-specific emission factors from co2data.fi database.

According to the calculation method, the LCA assessment covers areal, structural, and spatial parts of the building as well as the main parts of technical building systems. *Table 3* below shows the structural elements included in the calculation. In the table, the structural elements highlighted in green belong to the carbon footprint of the site while the other structural elements belong to the carbon footprint of the building.

Table 3. Structural elements included in the calculation.

Structural elements		Included in this calculation	Comment
Site elements	Ground elements	-	
	Soil stabilization and reinforcement elements	-	
	Paved and green areas	-	
	Site constructions	-	
Building elements	Foundations	-	
	Ground floors	x	
	Civil defence shelters	-	Not relevant
	Load-bearing walls	x	
	Columns	x	
	Beams	x	
	Intermediate floors	x	
	Roofs	x	
	Structural frame stairs	-	
	Façades	x	
	Windows	-	
	External doors	-	Not relevant
	External decks, balconies	-	Not relevant
	Roofing	x	Included in roofs
Internal space elements	Internal dividers, partition walls	-	Excluded
	Space surfaces	-	Excluded
	Standard fittings and fixtures	-	Excluded
	Flues and fireplaces	-	Excluded
	Box units	-	Excluded
Building services	Heating distribution system	x	Standard value for office (66 kg CO_2e/m^2)
	Fresh water and wastewater system	x	
	Ventilation system	x	
	Cooling system	x	
	Sprinkler system	x	
	Electricity distribution system	x	
	Elevators	-	

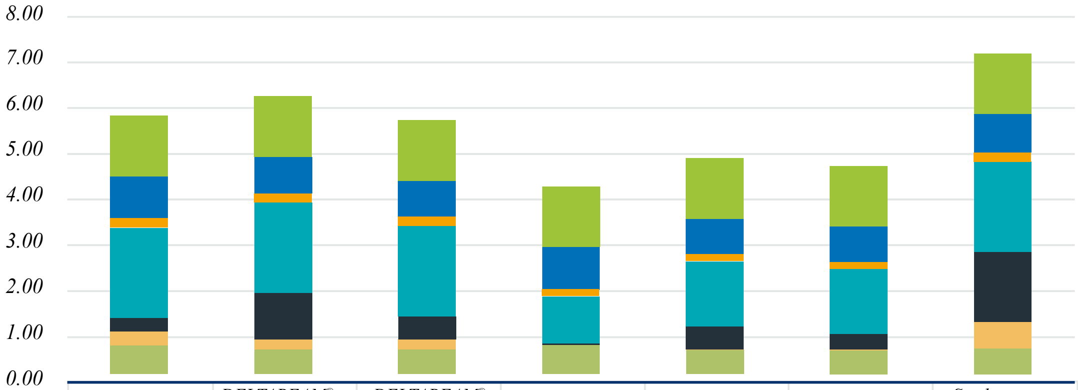
4.2. Combined results

The quantities of the different structural elements were determined using the Fenix calculation tool. Quantity data for structural elements in different design cases are presented below. When calculating the total emission impacts of the slabs possible top concrete or screed layer was taken into account in the calculations according to the structural build-ups. Carbon emissions were calculated based on quantity information and emission factors in national emission database or in EPD documents. For concrete beams, columns, walls, and solid concrete slabs emission data for reinforced precast concrete elements was used. Emission data sources are presented in more detail in appendix 1.

Table 4. Quantities of different structural elements.

Structure label	Beams	Columns	Walls	Façade	Ground floor	Slabs	Roof
Concrete element frame	1001 t	739 t	1840 t	6506 m^2	1083 m^2	9150 m^2 1680 m^2	1083 m^2
DELTABEAM® – concrete hollow-core frame	800 t	539 t	1582 t	5594 m^2	1083 m^2	9150 m^2 1680 m^2	1083 m^2
Timber frame	130 t	95 t	1865 t	6579 m^2	1083 m^2	9150 m^2 1680 m^2	1083 m^2
DELTABEAM® – timber frame	540 t	73 t	1543 t	5484 m^2	1083 m^2	9150 m^2 1680 m^2	1083 m^2
Steel – concrete hollow-core combination frame	266 t	99 t	1668 t	5898 m^2	1083 m^2	9150 m^2 1680 m^2	1083 m^2

This data was used to calculate the carbon footprint of the whole building in the lifecycle stages of A1 – A3.



	Concrete Element Frame	DELTABEAM® – concrete hollowcore	DELTABEAM® Green – concrete hollowcore	Timber frame	DELTABEAM® – timber	DELTABEAM® Green – timber	Steel concrete hollowcore combination
HVAC	1.32	1.32	1.32	1.32	1.32	1.32	1.32
Façades	0.93	0.80	0.80	0.93	0.78	0.78	0.80
Roof	0.19	0.19	0.19	0.15	0.15	0.15	0.19
Intermediate floors	1.98	1.97	1.97	1.02	1.43	1.43	1.97
Beams	0.29	1.01	0.50	0.03	0.51	0.34	1.54
Columns	0.32	0.23	0.23	0.02	0.02	0.02	0.54
Load-bearing walls	0.62	0.53	0.53	0.63	0.52	0.52	0.53
Ground	0.19	0.19	0.19	0.18	0.19	0.19	0.19

Figure 8. Carbon footprint of different building elements in lifecycle stages A1 – A3.

The energy consumption during the building's operating period has been estimated in accordance with the project's energy survey. The assessment period is 50 years. Total heating and cooling energy needed was determined to highest and lowest building and other scenarios were interpolated based on that. Annual energy consumption in each case is presented in *Table 5*.

Table 5. Total heating and cooling energy, annual.

Structure label	Building height (m)	Electricity (kWh)	District Heating (kWh)
Concrete element frame	42.8	537,555	464,347
DELTABEAM® – concrete hollow-core frame	36.8	538,290	446,851
Timber frame	43.3	537,496	465,747
DELTABEAM® – timber frame	36.1	538,378	444,751
Steel – concrete hollow-core combination frame	36.9	537,655	447,956

The environmental impact of the framing system was evaluated considering the heating energy evaluation results. The findings revealed that timber frame yielded the lowest carbon footprint both in whole life cycle and in phase A1 – A3. However, due to smaller climate impact in operational phase, DELTABEAM® Green + timber frame had only 3% larger total climate impact than timber frame.

In more detail, the carbon footprint of different frames in different life cycle phases (kg/m^2/a) are as follows:

Table 6. Carbon footprint of different frames in different life cycle phases (kg/m^2/a).

Structure label	A1 – A3	A4	A5	B4	B6**	C1 – C4	A1 – C4	Total CO_2 index
Concrete element frame	5.83	0.23	1.65	1.55	5.91	0.67	15.84	112
DELTABEAM® – concrete hollow-core frame	6.25	0.21	1.65	1.55	5.8	0.64	16.11	114
DELTABEAM® Green* – concrete hollow-core	5.74	0.21	1.64	1.55	5.8	0.64	15.59	111
Timber frame	4.29	0.13	1.66	1.55	5.92	0.55	14.09	100
DELTABEAM® – timber frame	4.91	0.16	1.66	1.55	5.79	0.58	14.65	104
DELTABEAM® Green – timber frame	4.73	0.16	1.66	1.55	5.79	0.58	14.47	103
Steel – concrete hollow-core combination frame	7.09	0.2	1.70	1.55	5.81	0.61	16.95	120

* DELTABEAM® Green's climate impact is evaluated based on EPD and so-called green concrete (70% emissions compared to generic concrete)

** heating and cooling

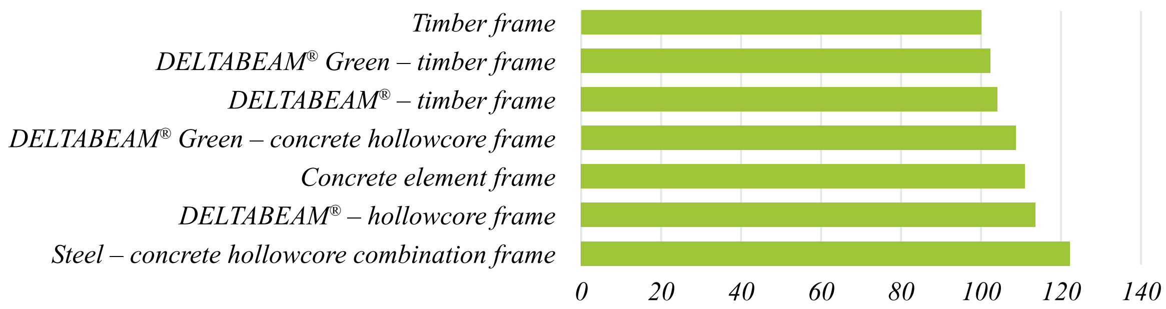
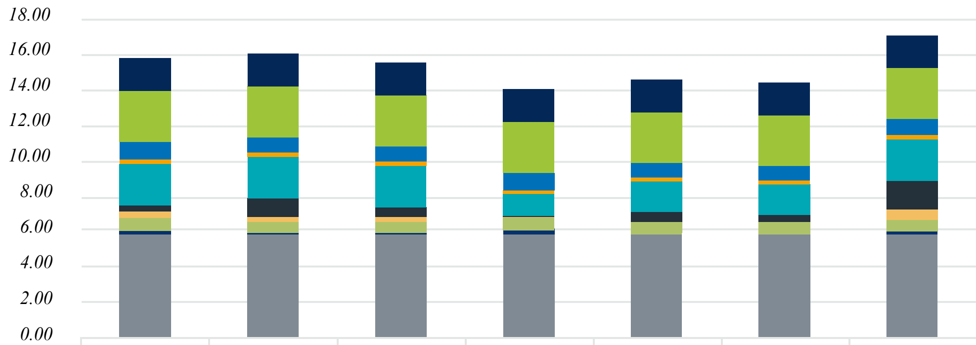


Figure 9. CO_2 index for whole lifecycle of different frames.

The breakdown from this data is presented in the following figure:



	Concrete Element Frame	DELTABEAM® – concrete hollowcore	DELTABEAM® Green – concrete hollowcore	Timber frame	DELTABEAM® – timber	DELTABEAM® Green – timber	Steel concrete hollowcore combination
Construction and demolition works	1.84	1.84	1.84	1.84	1.84	1.84	1.84
HVAC	2.86	2.86	2.86	2.86	2.86	2.86	2.86
Façades	0.98	0.85	0.85	0.98	0.82	0.82	0.85
Roof	0.26	0.26	0.26	0.22	0.22	0.22	0.26
Intermediate floors	2.33	2.32	2.32	1.24	1.73	1.73	2.32
Beams	0.35	1.06	0.54	0.05	0.54	0.37	1.60
Columns	0.36	0.26	0.26	0.03	0.03	0.03	0.56
Load-bearing walls	0.72	0.61	0.61	0.73	0.60	0.60	0.62
Ground	0.23	0.23	0.23	0.22	0.23	0.23	0.23
B6 Energy	5.91	5.80	5.80	5.92	5.79	5.79	5.81

Figure 10. Carbon footprint of different building elements, operational energy and construction works for the whole building lifecycle.

From these results we can see that the timber frame has the lowest carbon footprint in both the whole life cycle and in phase A1 – A3 (product stage). This suggests that timber is a more sustainable choice for framing systems when considering environmental impact.

However, it's also important to note that the DELTABEAM® Green + timber frame had only a slightly larger total climate impact than the timber frame (14.47 vs 14.09 kg/m^2/a), despite having a smaller climate impact in the operational phase (B6). This suggests that while the initial environmental impact of construction may be higher for some materials or systems (as indicated by the higher values in stages A1 – A3), their performance over time can result in a lower total environmental impact. On the other hand, the Steel - concrete hollow-core combination frame had the highest carbon footprint across all life cycle stages and in total (17 kg/m^2/a), indicating that this type of framing system may not be as sustainable as others without rigorous optimization.

5. DISCUSSION AND CONCLUSIONS

The study conducted a comprehensive analysis of different framing systems for a 10-storey office building, focusing on the structural design aspects, heating energy evaluation, and sustainability impact. The aim was to understand the effects of different frame solutions, particularly the thickness of the floor, on the sustainability of the building.

Integration of findings

The structural design was based on comparing different frame systems, with a focus on Peikko DELTABEAM®. The load analysis considered various types of loads, and material selection was based on structural performance. The energy design methodology evaluated heating energy consumption for two different frame systems (taller vs. lower buildings), and the results showed that changes in the external area of the building cause changes in heating and cooling demand.

The Life Cycle Assessment (LCA) methodology used in this study was comprehensive and rigorous. It considered various life cycle stages of the building, with an assessment period set at 50 years. The environmental impact of the framing system was evaluated considering the heating energy evaluation results.

Discussion of results

The study revealed that while all framing systems have an environmental impact, there are significant differences between them that should be considered when making decisions about building design and construction. For instance, timber frame yielded the lowest carbon footprint both in whole life cycle and in phase A1 – A3. However, due to smaller climate impact in operational phase, DELTABEAM® Green + timber frame had only 3% larger total climate impact than timber frame and significantly lower floor-to-floor height. Conversely, the frame made of a combination of steel and concrete hollow-core had the most significant carbon footprint in all life cycle stages, with a total of 17 kg/m^2/a. This suggests that this framing system might not be as environmentally friendly as other options without further optimizations.

One key result from this study is the required floor-to-floor height and total building height for each framing system. The data shows that the DELTABEAM® - timber frame had the lowest required floor-to-floor height at 3608 mm and total building height at 36.1 m among all options. This is significant as it indicates that using DELTABEAM® with timber can lead to more compact buildings without compromising environmental performance.

Recap of key findings and their significance

In conclusion, this technology white paper provides a comprehensive overview of the Life Cycle Assessment (LCA) conducted on a 10-storey office building using five different frame solutions. It presents detailed insights into the methodology used, the environmental impact of different framing systems, and combined results that offer a holistic view of their environmental performance over their entire lifecycle.

The key findings from this study highlight the importance of considering not just the initial environmental impact of construction materials and systems, but also their performance over time. This is particularly significant considering increasing global efforts to reduce carbon emissions and promote sustainable practices in all sectors, including construction.

Further study

Although there are numerous optimization possibilities for each frame solution, which could potentially offset the results, a considerable effort was made to ensure a fair comparison within the scope of this study.

The study was conducted with the assumption that the design spans were pre-set to 7 m × 7 m. Further research is required to determine whether there are any significant differences in the results when the design span is increased or decreased.

Based on the results, it can be hypothesized that increasing the span would have the following effects on the structure:

- The pure timber solution would no longer be feasible.
- The timber hybrid solution would remain competitive, but the slab height would increase drastically and solid CLT would be replaced with ribbed slabs.
- The concrete solution would be able to compete with structurally efficient slabs and rigid beams, but the beam height would still be a problem, utilizing ledgers would offset this problem up to certain limit.
- The concrete-steel hybrid would become more feasible, since the hollow-core slabs are able to function in longer spans and the steel beams would be able to provide enough rigidity without becoming too high.

If the spans were decreased to 5 – 6 m, the following structural implications would arise:

- The timber solution would become increasingly feasible.
- The timber hybrid solution would remain competitive to some extent, as the beams could be optimized.
- The concrete solution would not be able to compete due to the dimensions of concrete elements being uncompetitive in short spans.
- The concrete-steel hybrid would struggle to compete, as the steel beams would still have to carry the relatively heavy concrete slabs, which are already far from their optimal span.

From a sustainability perspective, it would be intriguing to investigate whether the differences in performance across various solutions would narrow, rearrange the order of solutions, or widen the gaps between the results. Additionally, incorporating architectural and space-use flexibility would add another dimension to this study.

In conclusion, if you want a SUSTAINABLE FRAME and wish to OPTIMIZE BUILDING LIFE CYCLE CARBON FOOTPRINT AND OPERATIONAL EMISSIONS use this checklist:

- ☐ Use products with low global warming potential GWP value (CO_2/kg or m^2 in environmental product declaration, EDP)
- ☐ Optimize amounts of all materials with design and consumption – avoid overdesign and waste
- ☐ Design efficient cubic efficiency
- ☐ Expand building's lifespan with a flexible layout and long spans in grid

It´s about sustainable space!