

Environmental impacts of early stage structure choices using Life Cycle Assessment

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ABSTRACT

In France, embodied carbon represents 35% (Pellan et al., 2022) of the total greenhouse gases emissions from the construction sector. This proportion can reach up to 70% when considering recent buildings ("Performance Énergétique des Bâtiments Neufs," n.d.). Diminishing environmental impacts of building's construction and demolition proves to be necessary to reach European environmental agreements. In particular, structural elements account for a large portion of material quantity and environmental impacts (Qarout, 2017). This article assesses building structures impacts in order to determine the importance of early-stage decisions regarding construction of housing and office buildings. To study the influence of materials, span and grid choices on environmental impacts, it combines the INIES database (French Environmental Product Declaration (EPD) database) and parametric buildings constructed with a set of precalculated structural elements composed of beams, columns, floor systems and foundations. Using Life Cycle Assessment (LCA) provides a more comprehensive picture of environmental impacts, expanding common energy analysis. Results are mostly influenced by structural typology and materials, and to a lesser extent by grid choices and span. Structural solutions can also better perform for a particular indicator while presenting higher impacts for another. It proves the necessity for designers to carry out holistic analysis.

Keywords

Structure, LCA, design, multicriteria, building

I. STATE OF THE ART

Environmental impacts of building structure have mostly been tackled through global warming potential evaluation (Basbagill et al., 2013; Hattan et al., 2015; Kaethner and Burridge, 2012). Comparison of structural systems have been made such as comparing the lateral loads resisting structural systems considering concrete or steel elements (Nadoushani and Akbar Nezhad, 2015). Many non-academic studies have been realised and provide an insight on the environmental weight of some structural typologies (Hattan, n.d.).

Many metrics have been developed to conduct those analysis. They depend mostly on the country where they come from. The Association of Structural Engineering IStructee in the United Kingdom has published a guide to assess the carbon footprint of structures ("How to calculate

embodied carbon (Second edition) - The Institution of Structural Engineers," 2022). In France, the RE2020 environmental regulation provides a framework to quantify the environmental impacts of new buildings. Each framework requires also a consistent set of appropriate environmental data, gathered in databases (De Wolf et al., 2020). In the case of the RE2020, the INIES database lists the environmental products declaration (EPD) of construction equipments and products used in France (Inies, n.d.). This database is filled by industrial companies and the declarations are verified by third parties organisms. The declarations are in accordance with the NF EN 15804+A1. LCA softwares such as ELODIE ("ELODIE by CYPE," n.d.) and NOOCO ("Nooco," n.d.) have also been developed to support civil engineers and architects in the design of buildings. Thornton Tomasetti also created the Design Explorer tool to test different constructive solutions using a multicriteria representation (Hristov, n.d.).

In practice, environmental assessment of buildings often focuses on climate change impacts only, neglecting other environmental impacts. Given the important material requirements of the construction and building sector, resource consumption as well as other Life Cycle Assessment (LCA) indicators needs to be taken in account. Moreover, even though LCA of complete buildings have been conducted in different studies (Blengini and Di Carlo, 2010; Soust-Verdaguer et al., 2016), a detailed parametric study of structures using an LCA methodology with multiple indicators has not been yet realised.

In this article the authors aim to evaluate which structures are the more environmentally performant. In that purpose a multicriteria analysis has been conducted using the LCA indicators provided by the EN15804 European standard. The article presents the influence of different structural parameters such as material, span and grid choices. The work was conducted considering a cradle to grave approach based on scenarios in a French context.

II. BUILDING STRUCTURE COMPOSITION AND CALCULATION

This article focuses on slab, beam, column and foundations (ground floor slab with stringer and footing). We only consider the vertical loads applied on those elements. First, we make a set of precalculated structural elements. This set covers a wide range of geometrical situations in order to compose a variety of building structures. Are considered housing situations with a live load load of 1.5 kN/m², associated to a specific acoustic value of 53dB for the floor systems. An equipment permanent load on the floor of 1.2 kN/m² due to the equipment is also taken into account, in addition to the self-weight of structural elements. Finally, a fire resistance of 60 minutes is accounted for. Those assumptions are as close as possible to the targets of an early-stage design. The functional unit considered is 1m² of exploitable floor.

a. Floor systems calculation

The floor system is composed of a deck above a beam frame. 3 different types of decking are considered: steel-concrete composite slab, cast in place concrete slab and CLT slab. Each slab consists in multiple layers detailed in *FIGURE 1*. For instance, a CLT slab is composed of a CLT panel and a concrete screed for acoustic purposes. It is important to consider those elements in order to compare different solutions at equivalent usages/with the same functionality. For instance, in a composite deck the concrete is used for both structural and acoustic purposes. To compare it to a CLT solution, a screed must be added to the latter.

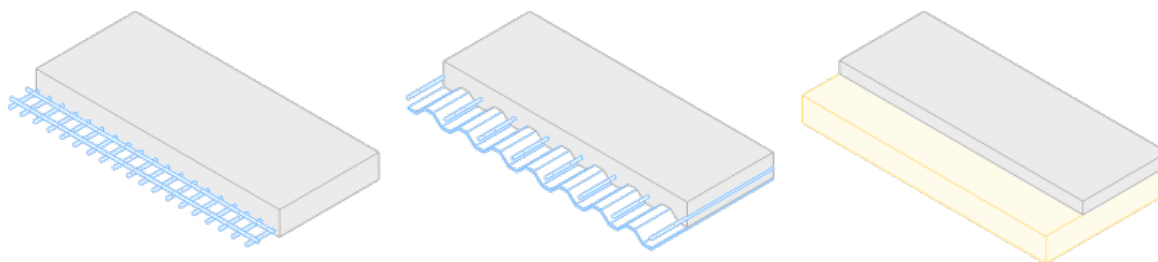


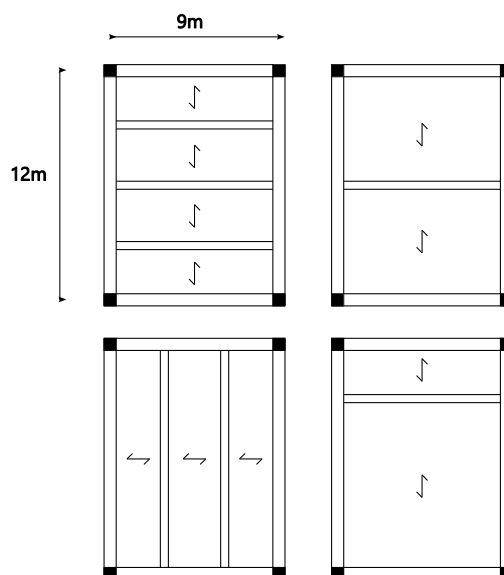
FIGURE 1 Deck Typologies from left to right: cast in place, mixed concrete and steel, CLT

TABLE 1 Span of deck typologies

Typology	3m	4m	6m
Cast in place slab	X	X	X
Mixed concrete and steel slab	X	X	
Cross Laminated Timber slab	X	X	X

A finite number of possible deck span are considered, depending on the typology of the deck so it fits its structural capacity (TABLE 1). These decks are calculated using different industrial charts.

We also considered a finite number of beam spans: 3m, 6m, 9m and 12m. This allows for a large panel of beam frames. For instance, we can cover a 9x12m² space floor with different ways if we use 3m or 6m deck spans and 3m, 6m, 9m or 12m beam spans (FIGURE 2). To choose from those geometrical possibilities, we computed an optimisation based on a mass criterion. The optimisation consists in computing all beam and deck arrangement options. We then calculate the total weight of each solution and chose the lighter one. This criterion is relevant when considering beam and deck that are made with the same material.



In order to be as close as design stage results, FIGURE 2 Dispositions for a 9mx12m floor we verified the beam maximal moment, displacement and lateral buckling using eurocodes NF EN 1995 for wood, NF EN 1993 for steel and NF EN 1992 for reinforced concrete.

b. Columns calculation

Columns have been calculated with:

- Three different material : glued laminated timber GL24h, steel S235 and reinforced concrete C20/25. Those are considered as standard structure materials.
- A height of 2.5m

- A range of ultimate limit state vertical load varying from 100 to 16000 kN

They have been verified using eurocodes NF EN 1995 for wood, NF EN 1993 for steel and NF EN 1992 for reinforced concrete. We only considered vertical loads hence verified buckling and axial stress. We consider steel connections for beams and columns in steel and wood that represent 10% of the mass of the elements according to practice experience.

c. Foundations calculation

Isolated piles are considered for foundations. Those are calculated following the EN 1997. Considering the formalism of NF P 94 261, piles must verify :

$$R_{v,d} = \frac{A_{eff}q_u}{\gamma_{R,d}\gamma_{R,v}}$$

Where A_{eff} is the effective surface of the pile, q_u is the ultimate strenght of the soil, $\gamma_{R,d}$ is the model coefficient, $\gamma_{R,v}$ is partial resistance factor. We consider our loads to be centered so $A_{eff}=A$. As we use a pressiometric method :

- $\gamma_{R,d}\gamma_{R,v} = 1.68$ at ULS
- $\gamma_{R,d}\gamma_{R,v} = 2.76$ at permanent and characteristic SLS

Also from (FRANK, n.d.)

$$q_u = k_p p_{le}^*$$

Where p_{le}^* is the equivalent effective pressure calculated at the depth $D+2/3B$ where D is the depth of the foundation, B the width of the pile, k_p is the pressiometric factor of bearing capacity.

We have

$$p_{le}^* = p_l^*(D + 2/3B)$$

$$p_l^* = p_l - p_0$$

with p_l the measured pressure and p_0 the horizontal stress before test.

Three preselected types of soils are specified in [TABLE 2](#).

TABLE 2 Soils considered with pressiometric characteristics

Type	Class	p_l (Mpa)	k_p
Clay and silt	A	0.7	1.30
Sand	B	1.5	2.25
Marl and calcareous marl	B	4.5	1.68

From the previous equation, considering a square footing the width B of the footing was deduced. The height h of the footing was calculated using :

$$h = \max\left(\frac{B - e_{column}}{4} + 0.05; 0.25\right)$$

with e_{column} the width of the column. Finally we consider a ratio of 50 kg/m³ of reinforcing steel.

d. Building structure composition

First the building structure is drawn with the software Rhinoceros 3D from Robert McNeel & Associates. The floors and beams are represented as one surface and the columns as lines. Each

structural element is put in a specific layer corresponding to its material or floor typology. Those geometrical elements are then transmitted to a python script via grasshopper. The python environment allows to create a specific data structure to evaluate the loads on each structural element. The calculations start from the top of the building to the foundations. The elements are calculated in the following order :

- The floor system is calculated following the equipment dead-loads and the variable loads
- The beams are calculated using the equipment and floor system dead loads and the live loads acting on the supported deck
- The columns are calculated using the dead loads from the equipments, floor system, beams, superior column and the variable loads of the superior floors. The variable loads are adapted using a reduction factor following NF EN 1991-1-1.

This process is synthesised in [FIGURE 3](#). This process works when the columns are aligned in the building.

From the geometry and the loads associated to each element we deduce the sections and materials quantities using the sets of precalculated elements.

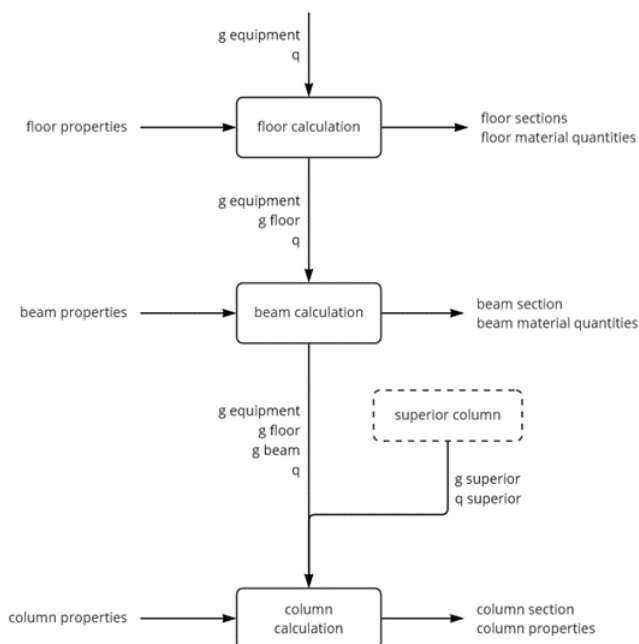


FIGURE 3 Diagram of building structure calculation where g are permanent loads and q variable loads

III. LCA DATA

The environmental study presented in this article is an attributional and static LCA of the building structure using a cradle to grave approach. Following the terms of NF EN 15978, a reference study period of 50 years for the building structures and a full renewal of the elements are considered. It means that, for 20kg of an element with a life span of 30 years, 40kg will be considered in the LCA. The environmental unit impact of the components comes from the INIES database.

The choices are detailed in [TABLE 3](#). Collective INIES EPD are used to better represent the materials that are used for construction in France.

TABLE 3 LCA EPD from INIES

Material	INIES data id
Steel	32207
Glulam	26812
Steel for connections	32206
Concrete with CEMII cement	27741
Reinforcing steel	30376
Metal sheet	32206
Cross laminated timber	27250
Concrete screed	12465

IV. CASE STUDY

A typical geometry of a housing building is used to test the influence of different parameters such as span and structure material. The building is five storeys high, each floor 2.5 m high, 36 m long and 12 m width.

From this geometry the building is sized using different structural frames. A frame is described as the position of the column elements. A floor complex above is then composed according to the principles of Section II. 6 building situations are studied with the following frame size : 12x12, 12x6, 12x3, 6x6, 6x3, 3x3 ([FIGURE 4](#)).

For materials the wood solution uses CLT as slab, glued laminated timber for beams and columns. Steel solution uses steel-concrete composite slab, steel S235 for beams and columns. Concrete solution uses cast-in-place slab, concrete C20/25 for beams and columns.

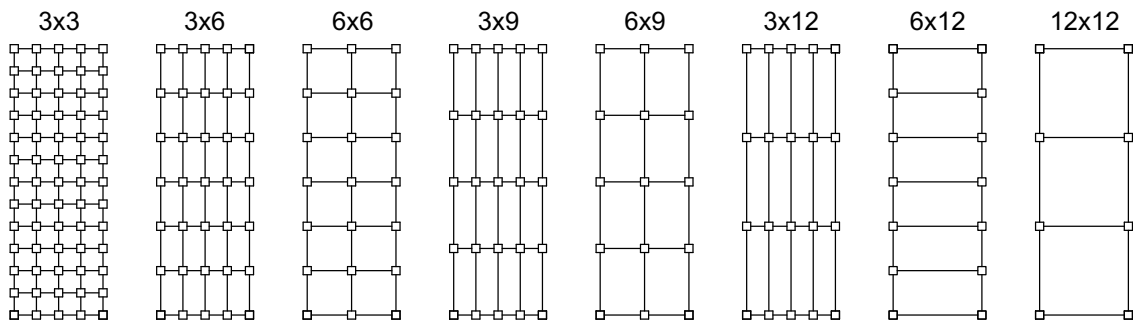


FIGURE 4 Frame situation of the case study

V. RESULTS

a. LCA results

Each typology has been calculated for a housing usage and with 60 minutes of fire resistance using the methodology described in II.c. From this basis the LCA of the building structures has been performed. Results are shown in *FIGURE 5*. The circles represent the chosen grid frame. The bigger the circle, the higher the span of the elements: the size of the circle is proportional to the sum of the span in the two directions of the slab.

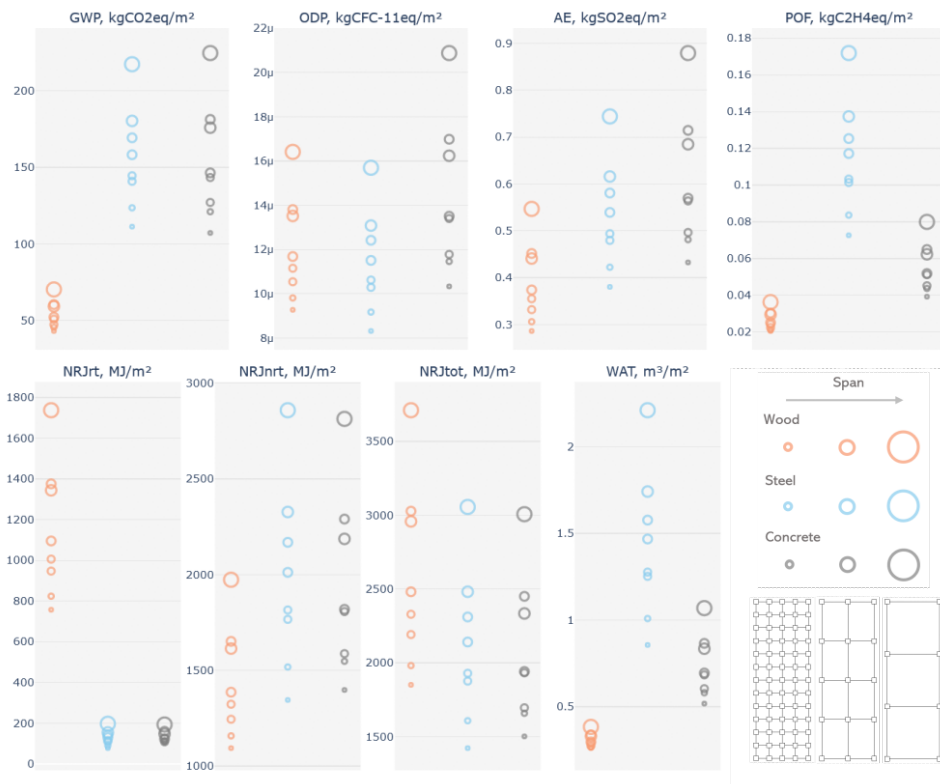


FIGURE 5 LCA results taking into account span and material ; GWP : global warming potential, ODP : ozone depletion potential, AE : acidification, POF : photochemical ozone formation, NRJrt : renewable energy consumption, NRJnrt : non renewable energy consumption, WAT : fresh water consumption.

We choose a reduce set of indicators from EN15804+A1 representing a diversity of behaviour in the results.

For every indicator we observe that the greater the span, the greater the impact. For GWP in the concrete case, the impact of the 12x12 configuration is 112% higher than 3x3 configuration's. Indeed, even with a reduced number of columns with higher spans, there is more mass in the beam and slab systems. As this last part constitutes a 2D element an increase in thickness is more impactful in term of mass quantities. However, there is an exception of this phenomenon for wood and concrete structure with the 12x6 grid having a lower impact than the 12x3 grid. For concrete, the 12x6 grid has an impact of 176 kgCO₂eq/m² whereas the 12x3 grid has an impact of 181 kgCO₂eq/m². This means that in this situation having a thicker deck is better than having more beams. It can be explained by the fact that, even if we have more beams, they need to have a minimal

size and this generates more material consumption compared to less but stronger beams and a thicker deck. This however is specific to this particular situation.

For GWP, steel and concrete solutions are much more impactful than wood, from 150% more for the 3x3 configuration to 224% more in the 12x12 configuration. Steel and concrete are more comparable and the best solution between the two depends on the span. Those impacts can be justified by the high CO₂ emissions from steel and concrete production.

For ozone depletion, the less impactful material is steel and the higher is concrete.

For acidification, concrete is the most impactful material followed by steel and then wood.

For photochemical ozone formation, steel solutions are the most impactful. This is due to the high emission of nitrogen oxides (NO_x) in the traditional converters.

For the flow indicator of consumption of renewable energy resources, wood solutions are the highest. It is since wood as a construction material is also considered as a potential energy source if we choose to burn it. It is not the consumed energy part that is high but the prime material that can be used as a renewable energy source.

For the consumption of non-renewable energy resources, steel solutions are the most impactful. This is due to the consumption of fossil fuels in traditional converters. Also concrete has an impact higher than wood solutions due to the production of clinker for the cement.

The total consumption of energy resources, which is the sum of the two preceding indicators, is higher for wood. This comes from the consideration of wood as a potential energy source as specified for the consumption of renewable energy resources.

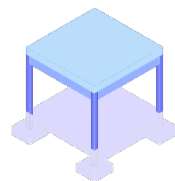
Concerning water consumption, steel solutions are the most impactful.

Considering the impacts with the EN15804 indicators, there is no absolute best material for building structures, since a given solution is better for a certain indicator, and worst for another. This choice should be made regarding the project aims and the indicators the client and designers want to focus on. Another way to choose would be using another Life Cycle Impact Assessment method using damage indicators, or normalisation factors (Crenna et al., 2017).

GWP results can be compared with values found in the literature. GWP ranges from 43 to 70 kgCO₂eq/m² for wood solutions, 111 to 217 kgCO₂eq/m² for steel and 107 to 224 kgCO₂eq/m² for concrete. Those results are in the range of (Hart et al., 2021) for wood but are lower than values of (De Wolf et al., 2016). Differences come from multiple factors, first, our study focuses on French based scenarios which has an influence on GWP of the materials. Our study is also limited to deck, beam, columns and foundations.

b. Impact repartition per element

The mass, GWP and ODP repartition between the different elements can be observed in [FIGURE 6](#) and [FIGURE 7](#) respectively. For each building grid typology impacts were computed for the three material solutions along with the mass of the structure.



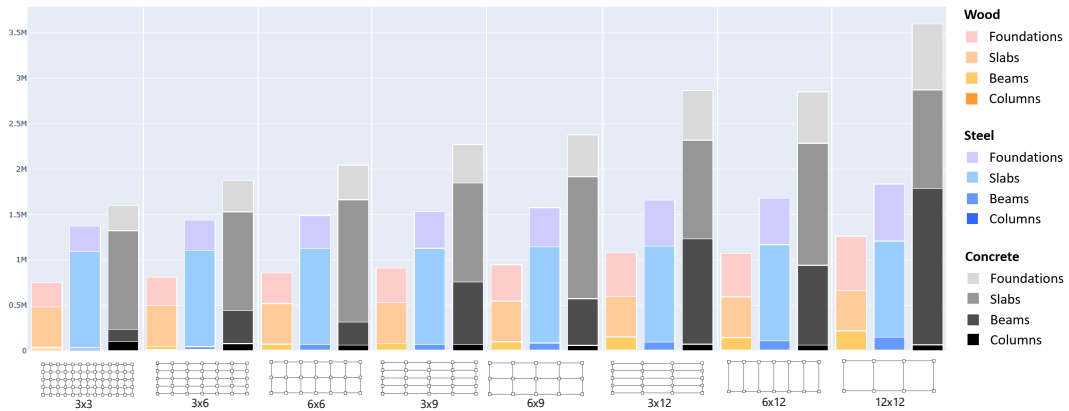


FIGURE 6 Mass repartition according to span and material (in kg)

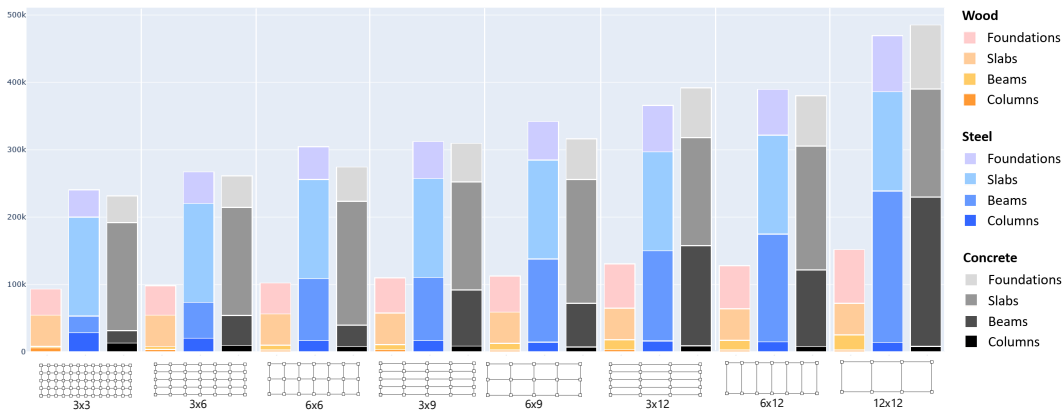


FIGURE 7 GWP repartition according to span and material (in kgCO₂eq)

The results show that the greater the span, the greater the mass and GHG emissions. Most of the mass and climate change impact are concentrated in the floor elements (slabs and beams). This proportion tends to change with longer spans for which beams take most of the impact. For GWP, slabs range from 30% to 70% of the total impact. This is due to the fact that the optimisation in II.a) tends to add beams instead of choosing higher span slabs. There is an exception in the concrete structures for the 6x9 frame for example, where beams contribute less to the total mass, which means that longer spans for the slab are chosen hence there are less beams in the structure.

Foundations constitute around 50% of the GHG emissions for wood solutions. This is due to the use of concrete in the foundations. The contribution of foundation is about 20% of the total impact on climate change for steel and concrete structures.

Column elements constitute a low part of the impact on climate change. For short spans, their contribution is similar to the beams’ ; around 10% for steel structures. However, this proportion diminishes drastically for higher spans; 1 to 3% depending on the material. This is due to the nature of the elements that are 1D compared to slabs that are 2D. Also as the span increases less columns are use. Even if the sections are more important it does not balance this number reduction.

IV. CONCLUSIONS AND PERSPECTIVES

This study highlights material and span as the most influential factors for the environmental impacts of a structure. Higher spans tend to have a higher impact no matter which indicator is used. However small spans reduce the possibilities in terms of space and comfort for the architect. Good design should be a balance between LCA impacts and the space created.

The repartition of mass and GWP impact is mostly concentrated in slab and beam elements. Foundations constitute also a high part of the impact especially for timber structures. Local optimisation at the scale of the monomaterial slab system shows that the preferred solutions tend to use more beam elements to reduce the span of slabs. This follows the idea that we use the material where it is needed, 2D elements tend to be more mass consuming. Hence using beam to concentrate the mass where it is needed seems to be the better solution.

Also, even if a material is better on an indicator such as GWP it doesn't mean it is the best for other indicators. As such, designers need to take into account these multiple impact indicators to design more environmentally friendly structures.

This article is limited to the study of EN15804+A2 indicators. It would be valuable to consider other indicators. For example, using only wood might not be possible for resources management purposes (Mishra et al., 2022). Also impacts that are harder to qualify should be taken in account such as landscape destruction with the extraction of sand. Extending this study to other foundation types and wall would also give a more complete view of the environmental impact of structures. The architectural space quality needs also to be discuss. A 3x3 frame isn't as generous as a 12x12 frame due to the number of columns per surface area. This parameter needs also to be considered when designing a building.

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