*Acta Polytechnica CTU Proceedings* **33**:504–510, 2022
https://doi.org/10.14311/APP.2022.33.0504


# HOW DESIGN CONCEPTS INFLUENCE CARBON FOOTPRINTS OF LOAD BEARING STRUCTURES

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Abstract.
In recent years, it has become essential to consider the total carbon footprint of a construction project. Commonly, the question has been: 'What is the best material to be used in this context?' In this paper we argue that this question is incomplete, not taking the complexity of design choices into consideration. This paper intends to share light on how to analyse some factors that influence the construction of buildings in order to contribute to climate change mitigation, taking this complexity into consideration. Calculation of fossil greenhouse gas (GHG) emissions for two load-bearing structures for office buildings in 4, 8 and 16 storeys with equal functional requirements; e.g. load bearing capacity, acoustic performance, fire resistance and adaptability are addressed. The main materials for the load-bearing structures are cross laminated timber (CLT) elements and precast concrete elements respectively. The result show that one cannot on a general basis conclude that either type of load-bearing structure cause less fossil GHG emissions. It is always important to consider the building design, functionality as well as external conditions such as location when considering different load-bearing structure materials.

Keywords: Carbon footprint, EPD, LCA.

## 1. Introduction

Over the last 30 years, Life Cycle Assessments (LCA) have been applied in the construction sector as the methodological foundation to evaluate environmental performance of construction works and materials over the life cycle [1–3]. Standards for both product and building level assessment are developed. For the latter, the European standard EN 15978:2011, specifies the calculation method for assessing the environmental performance of building [4]. For documentation of the environmental profile for construction products, EN 15804 provides the requirements to develop environmental product declarations (EPD) [5].

The system boundaries defined in EN 15978 are A1-A3 (product stage), A4-A5 (construction process stage), B1-B7 (use stage), C1-C4 (end of life stage) and D (benefits and loads beyond the system boundary). The approach covers all stages of the building's life cycle and is based on data obtained from EPD, their information modules, and when appropriate other information necessary and relevant for carrying out the assessment of the environmental performance of the building. To meet the increasing demands for GHG calculations of buildings in the Norwegian market, a standard, NS 3720:2018 that define the rules and requirements for calculation of so, is published by Standards Norway [6].

Moncaster et al. reviewed and analysed the data from over 80 individual life cycle assessments of buildings [7]. They found that several authors have used such findings to identify routes to lower carbon buildings. The strategy considered to have the biggest impact is the substitution of high carbon materials with low carbon; this is considered particularly important for the main structural and cladding elements which are often shown to have the highest impacts [8–10]. Others have found that adaptability and patterns of use are of more importance as design factors than the building materials and products themselves, as the latter are a consequence of those factors [11, 12]. Additionally, high replacement rates of materials with high embodied carbon as consequence of low adaptability will have a great impact on life cycle performance. The average rental period for office buildings in Norway is 7 years. Every seventh year, buildings are extensively rebuilt due to new tenants'needs and requirements [1]. How extensive the rebuilding processes will be will depend on the degree of adaptability of the building. Thus, design for adaptability for office buildings is of vital importance.

The goal of this study is to increase the knowledge regarding how design for adaptability, choice of materials and locations affect greenhouse gas calculations for load-bearing structures in office buildings.

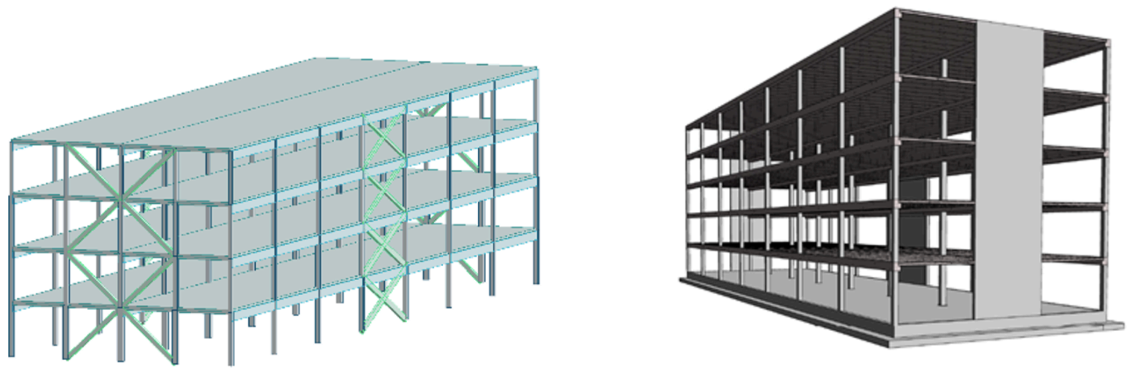

Figure 1. Illustration of the two different load-bearing structures for office buildings (wood-based structure to the left).

## 2. Methods

### 2.1. The objects

The objects under study are two load-bearing structures for office buildings in 4, 8 and 16 storeys respectively, with equal functional requirements; e.g. load bearing capacity, acoustic performance, fire resistance and adaptability for future changes.The design is similar for both the wood-based and the concrete based structure. A visualisation of the two alternative 4 storey load-bearing structures can be seen in Figure 1.

The floor area size per storey of 50.4 m × 15.9 m (801 $m^2$) was chosen based upon recommendations given in SINTEF Building Research Design Guides for Adaptable office buildings [13]. It includes guidelines for physical sizes such as building width and floor area as well as guidelines for flexibility in office buildings in connection with pillar locations, etc. A width of 15 − 17 m is optimal as it gives the possibility of different interior solutions and simultaneously an acceptable area efficiency [14]. Ideally, columns and load-bearing walls should be avoided in areas that can accommodate different types of workplace solutions to ensure high degree of adaptability. Based on building technical considerations, the optimal span for a building width of 16 m will be approx. 8 m. This means that a row of columns should be placed approximately in the middle of the building with a centre distance in the longitudinal direction of approx. 5 − 8 m. This recommendation is to limit the load and cross-sectional dimension of the beams, between the columns and the column itself.

It is assumed that foundations for all alternatives consist of the same concrete quality B35, placed in a humid environment below ground level. Finally, the soil type is assumed to be natural sandy for 4 storeys, and natural gravel for 8 and 16 storeys. The solution of the foundation in the study consists of a foundation slab at the two short sides.

The constructions experience the same magnitude of horizontal forces from wind, but the dynamic effect will be different since the stiffness and self-weight of the two alternative 16 storey buildings is different. The gables in the concrete solution are assumed to be of 12 m width, consisting of vertical, rigid concrete slabs, whereas the two short sides in the wood-base structure are assumed to consist of trusses along the width of the building (15.9 m). Volume of concrete walls in every gable is 126 $m^3$ (stabilizing effect from self-weight is about 2800 kN), whereas volume of trusses is 46 $m^3$ (stabilizing effect from self-weight is about 190 kN). This explains the increased need for ready-mixed concrete for 16 storey wood-based structure.

The fire requirements in Norwegian building regulation, TEK17 is used [15]. The regulations consider the constructions to be in hazard class 2, independent of the number of storeys, given that all storeys are used as office space. Fire design of the concrete solution would be unproblematic up until R120. This does not apply to wood-based constructions which have to meet requirements on design and measures. Proposed measures are (≥ R 60) 12 mm gypsum and 2 layers of 14 mm fire rated gypsum [16].

The load-bearing structures are designed by use of FEM-design by Strusoft and OS-prog and quantities are extracted from this and further organised in Excel, see Table 1 and Table 2 for material specification and quantities.

### 2.2. System boundaries

EN 15978 [4] and NS 3720:2018 [5] was used as the underlying rules for carrying out the calculation of the GHG emissions for the load-bearing structures. Several of the applied EPDs that are used as data source have not declared emissions connected to the C module (end-of-life). Therefore, it was chosen to limit the study to include only A1-A5 modules, from the extraction of raw materials to the construction of the load bearing structures. Building shell and façade system, non-bearing separating walls, or technical equipment such as ventilation, heating, sanitary

| Construction part | Material | 4 storeys | 8 storeys | 16 storeys | Unit | EPD number |
|---|---|---|---|---|---|---|
| Foundation | Ready-mixed concrete | 423 | 556 | 2 713 | tonne | NEPD-332-216-NO |
| | Reinforcement | 17 | 22 | 106 | tonne | NEPD-347-238-EN |
| | Columns | – | – | 31 | $m^3$ | NEPD-1577-605 |
| | Beams | – | – | 25 | $m^3$ | NEPD-1577-605 |
| | CLT-slabs | – | – | 203 | tonne | NEPD-345-236-NO |
| Vertical structures | Columns | 23 | 72 | 298 | $m^3$ | NEPD-1577-605 |
| | Truss | 11 | 23 | 109 | $m^3$ | NEPD-1577-605 |
| | Fireproof plasterboard | – | 20 000 | 41 550 | $m^2$ | NEPD-1264-406-EN |
| | Plasterboard | – | 10 000 | 20 775 | $m^2$ | NEPD-1260-406-EN |
| | Steel plate | 2.95 | 8.45 | 37.9 | tonne | NEPD-402-281-EN |
| | Bolts (steel) | 3.29 | 9.22 | 41.9 | tonne | NEPD-402-281-EN |
| Horizontal structures | Beams | 99 | 198 | 397 | $m^3$ | NEPD-1577-605 |
| | CLT-slabs | 813 | 1 626 | 3 252 | $m^3$ | NEPD-345-236-NO |
| | Steel plate | 3 | 6 | 11 | tonne | NEPD-402-281-EN |
| | Floor plasterboard | 3 100 | 6 250 | 13 500 | $m^2$ | NEPD-110-177-EN |
| | Insulation | 222 | 517 | 1 182 | $m^3$ | NEPD-1696-683 |
| | Elastic underlayment | 3 100 | 6 250 | 13 500 | $m^2$ | NEPD-207-260-NO |
| | Wooden laths | 18 | 43 | 99 | $m^3$ | NEPD-308-179 |

Table 1. Material amounts for the CLT-based load-bearing structure.

| Construction part | Material | 4 storeys | 8 storeys | 16 storeys | Unit | EPD number |
|---|---|---|---|---|---|---|
| Foundation | Ready-mixed concrete | 476 | 670 | 1 583 | tonne | NEPD-332-216-NO |
| | Reinforcement | 19 | 26 | 78 | tonne | NEPD-347-238-EN |
| | Columns | – | – | 79 | tonne | EPD generator |
| | Beams | – | – | 62 | tonne | EPD generator |
| | Hollow core slabs | – | – | 204 | tonne | EPD generator |
| Vertical structures | Columns | 47 | 124 | 565 | tonne | EPD generator |
| | Steel plate | 0.646 | 1.26 | 2.54 | tonne | NEPD-402-281-EN |
| | Bolts (steel) | 2.07 | 4.15 | 8.29 | tonne | NEPD-402-281-EN |
| | Wall panels | 102 | 409 | 1292 | tonne | EPD generator |
| Reinforcement | Reinforcement | 13 | 42 | 98 | tonne | NEPD-326-206-EN |
| | Prestressed reinforcement | 14 | 29 | 57 | tonne | NEPD-458-296-EN |
| Horizontal structures | Beams | 250 | 499 | 999 | tonne | EPD generator |
| | Insulation | 3100 | 1634 | 13 500 | $m^2$ | NEPD-00131E_ rev1_ROCKWOOL |
| | Hollow core slabs | 817 | 6250 | 3267 | tonne | EPD generator |

Table 2. Material amounts for the pre-cast concrete-based load-bearing structure.

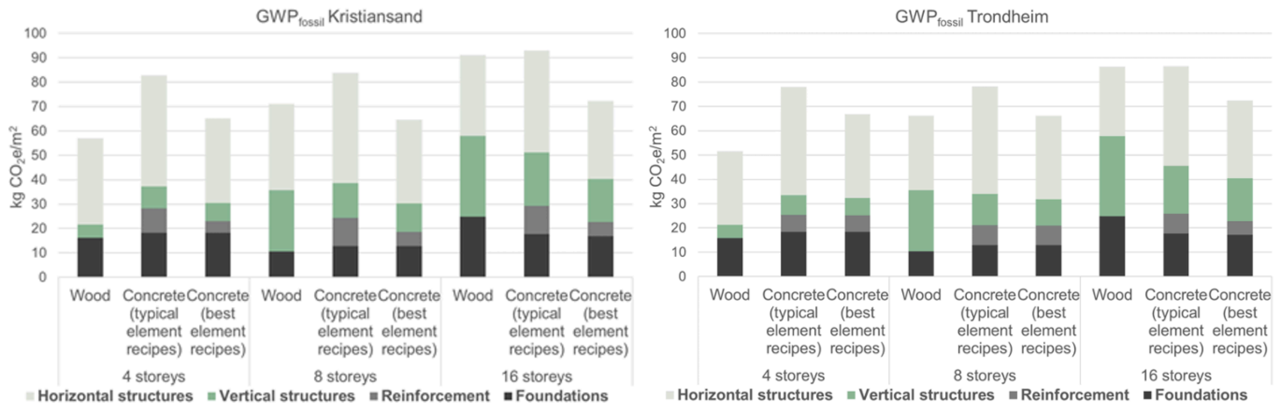


Figure 2. Fossil GHG emissions for three alternative load-bearing structures located in Kristiansand and Trondheim given as kg $CO_2e/m^2$

and electricity are not included, as it were considered independent from the load-bearing systems. The alternative structures are dimensioned for the same service life, being maintenance-free during the service life and that they will not affect the operational conditions of the buildings. Thus, the use phase (B1-B7) is excluded.

No assessment has been made of how large the contribution from the module C is, but Erlandsson and Malmqvist [17] demonstrated in their study that fossil greenhouse gas emissions related to demolition and waste management of concrete and wood-based buildings were in the order of $2-5$ % of emissions from A1-A5.

Carbon dioxide that is absorbed over time as the tree grows, is stored in wood-based building products during the life of the building [18]. When the buildings are disposed of after the end of their life and the wood-based products are used for energy recovery, the carbon is emitted in the form of $CO_2$. The climate change of sequestering biogenic carbon, storing it in harvested wood products and substituting more emission-intensive materials are hard to quantify. Although different methodological choices and assumptions can lead to different conclusions, there is no consensus on the assessment of biogenic carbon in life cycle assessment [19]. As we have not included end-of-life assessment, instant oxidation of biogenic carbon is used as the approach where biogenic carbon is considered "climate neutral". This is in accordance with the common practice with calculations that do not include all life cycle modules, and with the practice for GHG calculations for constructions [4, 18].

### 2.3. Environmental data

EPD for construction products published by EPD-Norway are used as data source for the GHG emissions for the building materials specified in Table 1 and Table 2. The amount of all materials used for the four-, eight- and sixteen-storey load-bearing structures are given in Table 1 and Table 2 for CLT- and pre-cast concrete structure respectively. EPD for construction products published by EPD-Norway are used as data source for the GHG emissions for the building materials specified in Table 1 and Table 2. Where more than one EPD for the same representative product was available, the product with lowest GHG emissions are used.

Emissions related to the A4 are usually calculated based on an average distance from the production site to a typical construction site in Norway, or to a specific destination such as Oslo. This means that the assumptions for A4 will vary and the values in the EPD cannot be applied directly. In this study, the construction sites are Kristiansand and Trondheim. GHG emissions were calculated based on the same type of means of transport as stated in the EPD. Our transport calculations also include infrastructure related to transport, which is not necessarily the case for all A4 modules in the EPD.

The precast concrete manufacturers in Norway use a pre-verified EPD-generator that allows for producing project specific EPDs [20]. Two different data set are used; average data from four different precast manufacturers'EPD for columns, slabs, wall elements and hollow cores respectively named 'typical element recipes'and EPD for the same product from the manufacturer EPD with the lowest GHG emission for A1-A3. For CLT slabs the manufacturer with lowest documented GHG emissions for A1-A3 is chosen.

## 3. Results

In Figure 2 GHG emissions per square metre for the wood-based and concrete load-bearing structures are given for all three storey heights located in Kristiansand and Trondheim respectively.

The results show that the wood-based structure has lower fossil GHG emissions than the construction with pre-cast concrete elements when built on four storeys for both locations but can be reversed at 16 floors when using the best precast concrete elements. For all cases, materials used for both vertical

| | Kristiansand | | | Trondheim | | |
|---|---|---|---|---|---|---|
| Element | 4 storeys | 8 storeys | 16 storeys | 4 storeys | 8 storeys | 16 storeys |
| CLT-slabs | 43 % | 34 % | 25 % | 36 % | 28 % | 21 % |
| Ready-mixed concrete incl. reinforcement (foundation) | 28 % | 15 % | 26 % | 31 % | 16 % | 27 % |
| Fire measures (plasterboard) | 6 % | 25 % | 19 % | 8 % | 27 % | 20 % |
| Steel products | 11 % | 12 % | 16 % | 13 % | 13 % | 17 % |

Table 3. Share of fossil GHG emissions in percentage from different construction materials in wood-based load-bearing structures of 4-, 8- and 16-storey located in Kristiansand and Trondheim.

| | Kristiansand | | | Trondheim | | |
|---|---|---|---|---|---|---|
| Element | 4 storeys | 8 storeys | 16 storeys | 4 storeys | 8 storeys | 16 storeys |
| Hollow core slab incl. reinforcement | 37 % | 37 % | 32 % | 37 % | 37 % | 31 % |
| Ready-mixed concrete incl. reinforcement (foundation) | 28 % | 20 % | 20 % | 28 % | 19 % | 45 % |
| Columns/Beams | 20 % | 18 % | 20 % | 18 % | 16 % | 46 % |
| Reinforcement | 7 % | 9 % | 9 % | 10 % | 12 % | 12 % |
| Wall element | 6 % | 12 % | 15 % | 5 % | 10 % | 15 % |

Table 4. Share of fossil GHG emissions in percentage from different construction materials in concrete load-bearing structures of 4-, 8- and 16-storey located in Kristiansand and Trondheim.

and horizontal structures contribute most. Table 3 and Table 4 present the contribution analysis to the total fossil GHG emissions in more details.

The contribution analysis shows that CLT-slabs, and foundation (ready-mixed concrete incl. reinforcement) contribute most to GHG emissions for the wood-based structure. The share of emissions from CLT decreases with the height of the building. Due to need for fire protection at higher storey, the contribution from plasterboard is significant. For the 8- and 16-storey structure, fire measures contribute with 25 % and 19 %, and 27 % and 20 %, of the total emissions for structures located in Kristiansand and Trondheim, respectively. Furthermore, GHG emissions from transport of CLT elements from the manufacturer in Sweden to Kristiansand accounts for 51% of the total GHG emissions from CLT (49 % for A1-A3). The distance to Trondheim is shorter, and the transport contribution from CLT is then 36%. This illustrates that transport to building site for heavy materials can be important for the results and is conformed by [21].

For the pre-cast concrete structure, hollow core slabs and columns/beams are the elements that contribute with the highest share of GHG emissions. Also, for the heavy hollow core slabs, transport turned out to be significant. The manufacturer that produce the hollow core slabs with significant lower GHG emissions than the competitors, is chosen only for deliveries to Kristiansand. The transport from production site to Trondheim gives GHG emissions that makes manufacturers closer to Trondheim favourable.

## 4. Discussion

The span of the construction in this study is set to 7.95 m. For solid wood constructions a span of 5 to 5.5 meters is an alternative to avoid dimensions that are too large. If the span length is reduced, the thickness of the slabs is reduced including column and beams dimensions, but there will be a need to add an extra load-bearing axis. Thus, the total material amount may not be significantly changed. Nevertheless, the structure will have a lower adaptability for changes and consequently lead to more materials e.g. when new tenants every seventh year require changes in the interior [2].

The gross area is representative for office buildings in Norway [13]. When assessing the higher structures, the choice of shape implies constraints for how the foundation and fire protection is solved. The foundation design is affecting the choices of materials and the material amounts as the structures. As the higher structures are relatively tall and slender (16 storey) the foundation will be subjected to large tensile forces. This can be solved by two different approaches; by friction piles or as in this study, by a casted underground concrete plate to ensure enough deadload to reach equilibrium. As the tensile forces are greater for the wood-based structures, the amount of materials in foundation used to ensure equilibrium are greater, which explains the GHG emissions (26 and 26 %) for the 16-storey wood-based structures. It is worth mentioning that there are also different solutions as to how the foundations of this specific construction design can be structured. A construction that has a different shape, on the other hand, will have different characteristics which will be best solved by utilizing a different approach

Due to the shape (tall and slender) of the higher structures, the building will have a propensity to oscillate due to wind forces. This is not taken into consideration in our study but may be a challenge for the highest wood-based structure. A possible remedy to satisfy the requirements on oscillation is to build weight and masses into the floors for the wood-based structure. However, this again will require more columns or increased dimensions for columns and beams that will affect the amount of material used.

Today's available technology for fire safety in wood constructions is assumed. As the technology develops on this area, the future solutions might be better and less material consuming, and it can potentially lead to a lower GHG emissions from the fireproof plasterboard used in the wood construction or solved by other technologies. However, research in the field of fire safety of CLT buildings concludes that there is a lack of knowledge for use of unprotected CLT [22, 23].

The fossil GHG emissions are highly influenced by transport and the choice of supplier used, as the elements for both the wood- and concrete-based structure are quite large. The shape of the elements leads to more transport than other materials. This shows a considerable potential for reduction of GHG emissions especially for large elements, and it is important to include transportation when requirements for GHG emissions are set.

It is pointed out that the fossil GHG emissions from material production and transport alone is not sufficient to conclude what is the most climate and environmentally friendly. The results of this study show that how the load-bearing structures are designed will considerably affect the GHG emissions related to both the load-bearing structure itself and the ability for design for adaptability for future changes in the office building. We want to emphasize in the study that based on the context and different solutions that are applied in specific projects, it will be possible to reduce the GHG emissions regardless of the material choices. This can be further promoted by giving manufacturers and other actors more room to use their skills and practical knowledge to develop innovative solutions. Giving the designers the opportunity to adjust the design of a construction in collaboration with manufacturers, will make it possible to develop innovative solutions and potentially a lower carbon footprint. The carbon footprint of a construction project will rely on the design and the materials chosen for the building, which in turn will affect the future need for materials for maintenance and lay premises for how extensive future renovation or refurbishment will be.

Can any general conclusions be drawn based on the results of this study? What is considered the best material or design choices with respect to climate change mitigation will be contextual for each unique construction. And even when assessing a load-bearing structure and not the whole building, a holistic approach is vital and one need to reflect on how the load-bearing structure will affect other activities'potential GHG emissions during the service life to ensure design for low GHG emissions.

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