Embody greenhouse gas emissions reduction for structural elements in office buildings

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Abstract. In order to reach the COP21 objectives, mitigation strategies must be identified in all economic sectors. In Austria, the construction sector represents one of the greatest sources of carbon intensive activities. Within this sector, buildings have a significant role to play. Through a systematic literature review, this paper identifies strategies to reduce the embodied carbon emissions of structural building materials. Then, by implementing the most promising alternatives in building case studies and performing a life cycle assessment, up to 15% reduction of the embodied greenhouse gas emissions was observed. This paper, however, intends to show that there is no technology that is intrinsically best at surpassing all others.

1. Introduction
Following the Paris Agreement, the EU member states have pledged to reduce their domestic greenhouse gas emissions by at least 55% by 2030 and 80-95% by 2050 (compared to 1990 levels) [1]. A commonly used approach to translate these goals into specific targets for the building sector is the introduction of a carbon budget. Various European countries have already calculated their building’s carbon budget [2] and a first estimate has recently been determined for Austria [3]. This budget includes the building’s operational emissions (electricity, heating, etc.), but also its embodied emissions (manufacturing of construction materials, transportation, end of life management, etc.)

Operational emissions have been the centre of attention for a long time as they used to largely surpass embodied emissions over a building’s life cycle. Today, with tighter regulations applying to new building standards and the design of advanced buildings, such as Nearly Zero Energy Buildings, operational emissions can be drastically reduced. As a result, embodied emissions are becoming increasingly significant [4]. Previous work on typical multi-storey buildings reveals that the structure, which includes the foundations, load-bearing walls, floors, and roof, is the main contributor to the overall embodied emissions of the building (accounting for 60-70% of total emissions) [5].

This paper, therefore, aims to bridge this gap by focusing on embodied greenhouse gas (GHG) emissions in structural building materials. First, a systematic literature review (SLR) was applied to identify strategies that have the potential to reduce the GHG emissions of structural materials in the building sector. With special attention placed on representativeness and data quality, the most promising technologies were then selected to further explore their influence on a building. For this purpose, an empirical case study of a multi-storey office building was modelled and analysed in-depth using the life cycle assessment (LCA) methodology. GHG reduction potentials were calculated at the building level and a sensitivity analysis on the allocation methods was performed.

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2. Methodological Approach

2.1. Systematic Literature Review – Data Collection

In this literature review, a systematic collection and analysis of studies carrying out LCA to investigate the improvement potentials of production and/or end-of-life treatment of construction materials was performed. Although the focus of this paper is on structural materials, the SLR had a wider scope and encompassed all materials that can be used in the building sector. A specific screen on structural materials was then applied as part of the selection procedure. Following the typical protocol for SLR [6], the search was guided by the following research question: which strategies for reducing embodied GHG emissions of construction materials have been investigated in the scientific literature and what is the maximal GHG reduction potential that can be reached? To fit this research question, the following keyword string was formulated: (LCA OR "life cycle") AND (low carbon OR sustainable material OR bio-based OR natural materials OR embodied) AND (building OR construction).

The databases Springer (Scopus) and ScienceDirect were selected to perform the SLR, which was executed in June of 2020 in the “Abstract, Title & Keywords” sections. No time limit was set, but grey literature and articles not written in English were excluded from the search. More than 1,500 scientific articles fitted these criteria. Thanks to a careful analysis of the titles and abstracts of each article, the number of relevant articles could be narrowed down to 669. Review articles were then separated from this pool for initial analysis, which provided a quick overview of the different strategies that existed. Relevant sources cited by these review articles which were not already in the search results could also be identified, as a snowball approach. Regarding the remaining articles, the ones focusing on structural materials were selected for a detailed reading and added to the pool of articles if relevant. The final sample for this SLR consisted of 58 articles and 254 case studies.

2.2. Systematic Literature Review – Data Analysis

In order to efficiently extract information from the case studies composing the final sample and to make the analysis of the results possible, a data extraction table was created. In this table, the following relevant data was collected: meta-data, characteristics specific to the investigated strategy, methodological aspects related to the LCA, LCA results, and GHG reduction potentials. It should also be mentioned that most of the studied articles compared their proposed technology to another which they consider to be conventional. Although the choice of this reference technology depends on the different articles and studied materials, the calculation of the GHG reduction percentage of the alternative compared to the given reference remains an interesting indication of the GHG reduction potentials that can actually be achieved for each strategy. Such a reduction potential was calculated whenever possible.

To then be able to choose the most promising technologies, the LCA results were harmonized to a mutual functional unit, which was relevant based on the type of material. Following harmonization, only the highly transparent case studies were kept to ensure the results were reproducible. For representative purposes, the studies carried out outside of Europe were then excluded. The remaining case studies were compared within corresponding functional units between identical LCA boundaries and allocation methods. For each combination, the technology with the lowest GHG emissions was selected. Two structural concretes (referred to as concrete mix A [7] and concrete mix B [8]) and two wooden materials (cross and glued laminated timber, CLT/GLT) were selected for further analysis.

2.3. Definition of the Building Case Studies

This analysis aims to quantify the impact resulting from the implementation of the identified strategies in the literature at the building level. The modelled case study is based on the structure of a seven-storey office building that was previously designed [9] in a reinforced concrete version (reference) and in a wooden version (GLT, CLT) following the Austrian building requirements. The wooden version also includes a central core built with reinforced concrete. To implement the two identified concrete mixes in the literature, special consideration was paid to their compressive strengths. For each mix, certain
The geometrical properties of the structure were adapted according to the Eurocode 2 (EN 1992) [10]. Additionally, for concrete mix B only, the level of detail in the article allowed for a modification of its composition: the amount of cement was reduced to fit the compressive strength of the reference concrete. Eventually, the assessed variations of the structure are the following:

1. The reference structure in conventional reinforced concrete.
2. The exact same structure in which the conventional concrete is replaced by concrete mix B (recalculated with reduced cement content).
3. The geometrically adapted structure to fit concrete mix B.
4. The geometrically adapted structure to fit concrete mix A. A sensitivity analysis on the allocation method (mass, economic or cut-off) was also performed for this alternative.
5. The wooden structure (GLT, CLT) including a concrete core made out of reference concrete.
6. The wooden structure (GLT, CLT) including a concrete core made out of concrete mix B (recalculated with reduced cement content).

2.4. Life Cycle Assessment Methodology

The LCA calculation was performed in compliance with the European norms overseeing LCA of buildings and construction products (EN 15978 [11] and EN 15804 [12]). The goal of this study is to assess the GHG emissions of different structural versions of a multi-storey office building. The functional unit is 1 m² (gross floor area) of a structure containing foundations, floors, roof, supporting columns or beams, and a central core. It is designed to support an office building containing seven storeys, considering usual working conditions in Austria, excluding the building’s surroundings, for a lifetime of 50 years. A cradle-to-grave analysis was performed. Operational emissions (B6/B7) were naturally excluded from the scope, as the focus is on embodied emissions. Replacement (B4) was not necessary and other modules (B1, B2, B3, B5, D) were not taken into account because of the lack of available data. The generic database used for this LCA is Ecoinvent 3.5, which is available in the SimaPro simulation tool. The production of concrete mixes A and B were modelled following the inventories given in the original articles. European generic data was taken to model the CLT and GLT. Global warming potential (GWP), expressed in kgCO₂eq, is the only considered indicator in this LCA and is calculated with the Environmental Footprint method version 1.0 (adapted). Finally, the modelling of biogenic carbon for the wooden elements follows the 0/0 approach.

3. Results and Discussion

3.1. Identified Strategies in the SLR and GHG Reduction Potentials at the Material Level

The analysis of the review papers resulted in the identification of four main strategies which can be implemented to reduce the embodied GHG emissions of structural materials in new buildings:

1. The use of bio-based materials, such as wood.
2. The use of inorganic natural materials, such as earth or stone.
3. The elaboration of a material based on a conventional technology, such as a concrete mix.
4. The integration of circularity approaches, such as the reuse of construction materials.

Figure 1 displays these results, including all the collected case studies, before the harmonisation of the results was completed. In the first half of this graph, the size of each flux is proportional to the number of case studies, which can be categorized by the strategy where the flux is headed. Strategies 3 and 4 have been largely studied by the literature in comparison to strategies 1 and 2. This was expected, as natural materials tend to be more investigated for insulation purposes than structural applications. In the second half, the fluxes lead towards the percentages of GHG emissions reduction achieved by the case studies. The size of each flux is proportional to the number of case studies having actually reached that percentage. As aforementioned, the choice of the reference technology from which the GHG potentials were derived depends on the different articles. A few case studies, especially within strategies 2 and 3, reach high GHG reduction percentages (80%-100%). As to the other case studies, the majority lies in the interval 0%-60%.
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Figure 1. Overview of the identified strategies and the GHG emissions reduction potentials.

When looking into the investigated materials, structural concrete was the most studied in the literature with 107 cases. Following the selection procedure, the first identified concrete mix (A) incorporates fly ash and recycled construction waste. It achieved a GHG emissions reduction of 25% compared to the conventional technology used in the study [7]. Concrete mix B contains fly ash, ground granulated blast furnace slag, and a limestone filler. It achieved a GHG emissions reduction of 80% compared to the studied reference mix [8]. As for natural materials, earth stood out for its impressively low embodied carbon, but was left out of the implementation at the building level as no articles from the studied sample applied this construction technique to multi-storey buildings. Stone was almost not studied at all in the collected sample. Wood was the most examined natural material, and most of the investigated technologies were GLT and CLT. Other studies assessed masonry elements but did not give enough details to allow for a relevant comparison between them. Certain elements still seemed promising, such as foam and cellular concrete or stabilized earth bricks. Uncertainties nonetheless remain regarding the possibility of using some of them as structural elements. Finally, additional technologies which are today at an early research phase, such as basalt fibres reinforcing bars [13], could lead to interesting GHG emissions reductions compared to traditional steel rebars. A lack of transparency in the methods did, however, not allow for the reproduction of the announced results.

3.2. Results at the Structural and Building Level

The GHG emissions reduction percentages achieved for the case studies are provided in Table 1 at the material, structural, and building levels. Wood could not be directly compared to concrete at the material level, as no common functional unit would allow for fair comparisons. To scale up the results from the structural level to the building level, an estimation was used based on a previously mentioned study which revealed that the structure accounts for approximately 60-70% of the GHG emissions of the building [5]. This ratio was applied to the reference structure to estimate the additional GHG emissions due to the other elements. The results at the material level and structural level were, therefore, directly obtained from the LCA, while the results at the building level were estimated from the LCA results of the structural level. Overall, the implementation of the identified strategies led to a reduction of GHG emissions when compared to the reference building. All the structures in which a non-conventional concrete mix was implemented have lower GHG emissions than their wooden counterparts. Further analysis will be carried out to identify the causes of these results. It should also be noted that, while at the material level, the maximum amount of GHG emissions reduction is 65%, it is only 23% at the structural level and 15% at the building level. These achieved values are, however, a first step towards compliance with the carbon budgets calculated for the building sector [3].
These results reveal that the methodological choices in the LCA can drastically change the outcome. The case study with mass allocation led to the highest GHG emissions of all the alternatives, whereas the case study with the cut-off approach led to the lowest. Because of this strong variability in the results, no technology specifically stands out from all the others in these case studies and no strategy could be deemed universal, although most of them seem promising by granting reductions in GHG emissions. A careful approach is, therefore, recommended when deriving conclusions from the previously shown results, especially when aimed at political decision making. As opposed to a universal strategy for all buildings, a case-by-case analysis should be encouraged.

Table 2. Sensitivity analysis on the allocation method at the structural level.

| Case study | GHG emissions reduction at structural level |
|------------|------------------------------------------|
| Case study 1 (reference) | 0% |
| Case study 4 (concrete) – Mass allocation | -36% |
| Case study 4 (concrete) – Economic allocation | 17% |
| Case study 4 (concrete) – Cut-off approach | 23% |
4. Conclusion
The first results of this paper were obtained through a typical SLR, which allowed for the identification of different strategies that could be applied to decrease the embodied GHG emissions of the structural building materials. Four major embodied GHG reduction approaches were identified: the use of bio-based materials, the use of inorganic natural materials, the elaboration of a material based on a conventional technology, and the integration of circularity approaches. Within those strategies, specific materials were singled out, such as concrete mixes containing supplementary cementitious materials and recycled aggregates, or wooden materials such as CLT/GLT. Reductions in GHG emissions of more than 80% were reached at the material level with the most promising technologies.

The implementation of these identified strategies in the case studies and their LCA led to a maximum reduction of 15% in GHG emissions for multi-storey office buildings in comparison with a conventional concrete building. These newly designed buildings are a first step towards the achievement of the COP21 goals. This study, however, underlines the fact that there is no intrinsically best technology that surpasses all alternatives. In particular, the use of wood does not constitute a universal solution and, under certain conditions, structures incorporating non-conventional concretes can have lower GHG emissions than wooden structures. The sensitivity analysis nonetheless exposed the high variability of the results depending on the allocation method adopted for the LCA. This parameter and the derived results from the LCA calculations should, therefore, be handled with care.

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