Embodied GHG emissions of reinforced concrete and timber mid- and high-rise structures: Driving factors and target values

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Abstract

In order to deliver on the commitments made on the Paris Agreement and limit global warming to 1.5ºC, it is necessary that greenhouse gas (GHG) emissions have been limited to net-zero by 2050. Monitoring and regulating life cycle emissions will be an important step in this direction, especially those considered as embodied. This study investigates the influence that different factors have on the embodied GHG emissions from material production of reinforced concrete and timber mid- and high-rise structures, through a meta-analysis with 62 cases, and establishes reference and target values for them. The results show the structural weight of buildings being the driving factor of embodied emissions. The benchmark comparison of the cases with the SIA 2040 targets further revealed that reinforced concrete buildings material production consumes most of the budget for embodied emissions. Opting for a timber structure can increase the available budget for the other components and life cycle stages of the building and, in some cases, can make the difference between meeting and not meeting the benchmark. Based on the 50th and 5th percentiles of modelled distributions, the reference and target values are, respectively, 3.7 and 1.7 kgCO$_2$-eq/m^2.y for reinforced concrete structures, and 1.2 and 0.4 kgCO$_2$-eq/m^2.y for timber structures. In addition, the creation and introduction of a 'carbon' label was also demonstrated to be a clear way of informing the environmental performance of buildings in terms of Global Warming Potential.

Keywords: Benchmarks; Buildings; Construction; Embodied carbon; Environmental impacts; Greenhouse gas (GHG) emissions; Life cycle assessment (LCA); Reinforced concrete; Timber

1. INTRODUCTION

Human activity is very likely the main cause of global warming; with recent anthropogenic greenhouse gas emissions (GHG) peaking (IPCC, 2014a), and climate change impacts on human and natural systems being observed across all continents and oceans, it has become evident that human activities need to undergo a behavioural change (IPCC, 2014b). In December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) agreed upon the adoption of the Paris Agreement, which settled to limit the global average temperature increase to well below 2 ºC and strive to achieve a 1.5 ºC target above pre-industrial levels (United Nations, 2015). With the motivation to provide a deeper insight into these matters, UNFCCC invited the Intergovernmental Panel on Climate Change (IPCC) to provide a special report on the global greenhouse gas emission reduction pathways, demonstrating the urgent need of "rapid and far-reaching transitions" across all sectors (IPCC, 2018).

The buildings sector plays a major role in this journey towards a carbon-free future, since it is one of the main contributors of GHG emissions to the atmosphere; according to 2019 Global Status Report by UN Environment and International Energy Agency (IEA), in 2018 buildings construction and operations constituted 36% of global final energy use and 39% of energy- and process-related CO$_2$ emissions (IEA, 2019). In recent years, efforts towards increasing building operation's efficiency through stricter regulation have successfully reduced buildings energy use. This reduction intensified the embodied share of emissions (i.e., the emissions stemming from materials and building production), especially in highly energy-efficient buildings (such as passive houses). Therefore, it becomes clear that attention must shift from an operational efficiency perspective to a holistic life cycle approach, with a special focus on embodied GHG emissions; IPCC fifth assessment report suggests substituting concrete and steel in buildings construction with timber as a mitigation measure (IPCC, 2014a).

The most recent UN population projections estimate the world's global population to increase from 7.8 billion (2020) to 9.7 billion by 2050 (United Nations - Department of Economic and Social Affairs - Population Division, 2019). Of these, 68% are expected to live in urban areas, resulting in an absolute growth of 2.2 billion inhabitants. Consequently, guaranteeing housing for all whilst simultaneously limiting anthropogenic GHG emissions to meet the global mean temperature increase target of 1.5 ºC, has become the new challenge. This need for housing in already densely populated areas will create a demand for new mid- and high-rise construction (i.e., buildings from 4 to 12 storeys and taller than 12 storeys above ground, respectively), in line with strict legislation to monitor and regulate its embodied emissions, ensuring the achievement of the Paris Agreement. Several countries have already began introducing the mandatory assessment of GHG emissions of buildings and some have even established emission caps or are planning to (e.g., France, Denmark, Finland and Sweden) (BPIE, 2021; Frischknecht *et al*., 2019; Trigaux *et al*., 2021). At European Union level, if the proposed revision of the Energy Performance of Buildings Directive (EPBD) is approved by the European Parliament, the assessment of new buildings' Global Warming Potential (GWP) will become a requirement by 2030 (European Comission, 2021a). Since the Buildings' structure can be one of the main contributors to the embodied emissions of buildings (Dokka *et al*., 2013; Kaethner and Burridge, 2012; Wallhagen *et al*., 2011; De Wolf, 2014), establishing reference and target values for the material production of structures will empower building designers to have a better sense of how to optimise their design, with the minimum possible impact, minimizing the whole GWP too.

This thesis aims to provide answers for the following three questions:

1) How do different factors influence the embodied GHG emissions from material production of reinforced concrete and timber mid- and high-rise structures at a large scale?
2) What are the current reference values of embodied GHG emissions from material production of reinforced concrete and timber mid- and high-rise structures, and what minimal values are presently possible to attain?
3) How can timber structures assist designers in meeting embodied GHG emissions budgets?

To attain these final goals, there have been established specific mid-term objectives, along with a well-defined methodology.

Initially, a sample of reinforced concrete and timber cases will be collected from literature based on a systematic literature review and a statistical analysis will be performed, to identify the range of values of embodied GHG emissions and structural weight of the two systems and to investigate the influence of different factors on those variables.

After thoroughly exploring the data, the embodied GHG emissions of the cases will be compared to a top-down benchmark in order to assess their performance. Subsequently, the data will be modeled with fitted distributions and from those models, reference and target values for embodied GHG emissions, from material production, will be define for reinforced concrete and timber structures. In addition, taking into consideration the performance of the cases, a labelling system will be designed from an annual per capita emission budget to rate the environmental performance of structures in terms of climate change impact and provide a clear way of comparing different systems.

The remainder of this paper is organized in four sections: Previous Work, Analysis of Embodied GHG Emissions and Structural Weights, Benchmarks for the Embodied GHG Emissions, and Discussion and Conclusions.

2. PREVIOUS WORK

Previous studies have already built up a considerable body of knowledge around the carbon footprint of structures, consisting of a powerful tool for this to be regulated, according to well-known ranges of values of embodied GHG emissions.

In the analysis of Simonen *et al*. (2017) regarding embodied emissions from the extraction and manufacture of materials, the results indicated that the carbon footprint of structures in general varies between 6.3 and 10.5 kgCO$_2$-eq/m^2.y, and between 5.7 and 10.2 kgCO$_2$-eq/m^2.y if only considering the superstructure (for a reference study period of 50 years). Taking a similar approach, De Wolf *et al*. (2015) investigated the embodied GHG emissions and material quantities of structures, in an attempt to provide building designers with a basis for comparison. The findings showed that for steel, reinforced concrete and timber structures, respectively, the material quantities range between ~700 and ~1,335 kg/m^2, ~890 and ~1,470 kg/m^2, and ~190 and ~265 kg/m^2, while the embodied GHG emissions range between ~5.0 and ~12.4 kgCO$_2$-eq/m^2.y, ~4.4 and ~8.7 kgCO$_2$-eq/m^2.y and ~3.6 and ~5.4 kgCO$_2$-eq/m^2.y (for a reference study period of 50 years).

The climate change impact difference between structural systems, investigated by Hart *et al*. (2021), by systematically comparing the total life cycle embodied GHG emissions of steel, reinforced concrete and timber superstructures, showed that the emissions from material production account for most of the climate change impact of superstructures, ranging between ~2.7 and ~4.2 kgCO$_2$-eq/m^2.y for a steel frame, ~2.1 and ~3.0 kgCO$_2$-eq/m^2.y for a reinforced concrete frame, and ~0.9 and ~1.1 kgCO$_2$-eq/m^2.y for a timber frame (for a reference study period of 50 years). However, emissions from other stages (end-of-life of timber systems that are landfilled) are not negligible and should also be considered in order to determine the real impact of structures; on average, material production constituted 75%, 70% and 42% of the total life cycle emissions of steel, reinforced concrete and timber frames, respectively — the low value of timber structures is a result of assuming a landfill scenario at the end-of-life.

Skullestad *et al.* (2016) compared the climate change impact (*$kgCO_2$-eq*) of four buildings with different heights (3, 7, 12, and 21 storeys) designed with identical loading conditions for a reinforced concrete and a timber frame. The study showed that the reinforced concrete structures were outperformed by the timber alternatives in all situations, yielding emissions savings ranging from 34% to 84% and averaging 63%, with an overall avoidance of emissions, when the substitution of fossil fuels with biomass from deconstruction waste was accounted. In addition, buildings taller than 12 storeys appeared to have a height premium, regardless of the type of structure. To resist the more substantial lateral loads, structures require larger quantities of structural materials per unit floor area, leading to an increase in embodied emissions; in timber structures, however, this effect was much less prominent.

Cattarinussi *et al*. (2016) compared two identical high-rise buildings, one designed with a conventional reinforced concrete structure and the other with an innovative post-tensioned timber frame (with reinforced concrete basements and core, for horizontal bracing). Additionally, the timber building had a shallow foundation, while the reinforced concrete version required a pile foundation due to its heavier weight. After material production, the embodied GHG emissions of the timber design were almost 45% lower than that of the reinforced concrete counterpart — but only 17% of the emissions were actually attributed to timber, the other 26%, 32% and 25% arose from the production of steel, concrete and non-structural materials such as screed, respectively.

Finally, other studies have shown that a reduction in embodied GHG emissions does not have to come necessarily from a change of structural system, but also from the structural designs of reinforced concrete buildings. Precisely, a shear wall frame and a decrease of the building height showed both a decrease in embodied GHG emissions, compared with those with a moment resisting frame (Nadoushani and Akbarnezhad 2015a; Nadoushani and Akbarnezhad 2015b).

3. META-ANALYSIS: ASSESSING THE INFLUENCE OF DIFFERENT FACTORS ON EMBODIED GEMISSIONS

The research methodology employed in this work follows the criteria of a meta-analysis, for the purpose of integrating findings from a large collection of individual analysis. Each step of the methodology is described in the following sections.

Scope

The scope of this study was limited to the environmental impacts of buildings' structural frame (i.e., substructure and superstructure) of mid- and high-rise buildings (i.e., buildings from 4 to 12 storeys and taller than 12 storeys above ground, respectively). Therefore, the system boundaries were limited to the structural materials of buildings. The term "structural materials" should hereafter be understood as referring to the materials composing the load-bearing elements (foundations, columns, load-bearing walls, girders, beams, and slabs), and, therefore, for the reinforced concrete buildings should encompass concrete and reinforcing steel. For the timber buildings, in addition to the concrete and reinforcing steel used in the foundations, basements and, in some cases, in the core, the structural EWPs, such as, CLT, glulam or LVL were also added; as for the steel connections, if they were included and reported by the studies, they were also considered to be a structural material. Materials such as screed and gypsum-based products were not considered to be in this group, due to their non-load-bearing function.

The life cycle modules that were included in this study were only those related to the manufacturing of the building materials (i.e., A1 to A3). The construction process modules (i.e., A4 to A5) were left out of the analysis, for comparison purposes, as well as the end-of-life stages, due to the lack of studies providing that information.

The unit chosen, for this study, as the reference unit to measure the building's embodied GHG emissions was *$kgCO_2$-eq/m^2.y.*, consisting of a variation of the classical *$kgCO_2$-eq* (kilograms of CO_2 equivalent). Recently, studies have been using this unit as a benchmark unit for the purpose of comparing the operational and embodied impacts of different buildings (Röck *et al*., 2020b; Röck *et al*., 2020a; Habert *et al*., 2020; Hoxha *et al*., 2020). It allows the normalization of the carbon footprint of buildings by a common floor area unit, i.e., square meters of gross floor area (m^2 GFA), and by a reference study period of 50 years.

Literature review

Since a research activity related to the international project IEA EBC Annex 72 had already conducted a quite extensive systematic compilation of scientific literature, that was well documented, this study used its database as a basis to build on. This database was first developed by a systematic search and followed by a snowball approach, that, in addition to checking the reference list of each article, assessed case studies listed in European technical reports and consulted experts in the field for additional input regarding relevant LCA studies (Röck *et al.*, 2020b).

Building on the systematic search performed within the IEA EBC Annex 72 project by Röck *et al.* (2020b), a second snowball procedure was carried out using the sample of literature obtained from it as a starting set. This time, however, the scope of the search was narrowed by the following exclusion criteria:

- Studies that did not specify the structural frame embodied GHG emissions or provide enough information to enable its calculation;
- Studies that either failed to report both the cases' gross floor area (GFA) and net floor area (NFA) or that did not provide floor plans that could be used to calculate these.

This second snowball procedure was finalized in May 2021 and resulted in 50 studies added to the initial sample after title and abstract review and 21 after full article review. In total, this additional sample contained 11 scientific papers, 6 reports, 3 master theses and 1 doctoral thesis, summing a total of 55 cases. The final database, organized in a Microsoft Excel file, followed the same structure as the original list provided by Röck *et al.* (2020), detailing the studies' source, author(s), year of publication, title, journal title and DOI/reference.

Data extraction

To decide what data would be relevant for the upcoming analysis, three main points were set to be important within the scope of the study: methodology of the assessment, building characteristics and structural frame's embodied GHG emissions. Developing on these three main aspects, 13 fields were added: 7 related with the methodology adopted in each study (Methodology; Impact Assessment Method; Database; Software; Floor Unit; Reference Study Period; and Assessed Structure), 5 detailing the assessed building characteristics (Main material of structural system; Number of floors; Location; Type of use; and Structural weight [kg/m²]) and 1, comprising 17 subfields, one for each life cycle module, reporting the GHG emissions throughout the building life stages.

Due to the heterogeneity of the studies and different ways of reporting data, those where the embodied GHG emissions of the structural frame could not be obtained directly had to be calculated with one out of two approaches: based on the percentage contribution of the structural frame or using the structural materials quantities and respective emission factors.

The first approach relied on the total embodied GHG emissions and on the percentage contribution (PC) of the structural frame. In the cases where the total value of embodied GHG emissions was not divided into percentage contributions per building elements but instead by building materials the structural frame's PC was deemed equal to the sum of the structural materials' PC. Once a PC of the structural frame was available, it was multiplied by the total embodied GHG emissions to yield the structural frame absolute contribution (AC). In the cases where the AC of the building materials was directly available, the structural frame's embodied GHG emissions were calculated just by summing the structural materials AC.

The second approach calculated the GHG emissions of the structural materials from their origin, i.e., making use of the physical material quantities used in the building construction, in m^3 or kg, and the respective emission factors ($kgCO_2\text{-}eq/m^3$ or $kgCO_2\text{-}eq/kg$).

Data harmonization

At the end of the extraction process, the data was equally organized for all studies but was still lacking comparability. To resolve this issue, the GHG emission values had to be brought to a common reference unit that, as already explained, was chosen to be $kgCO_2\text{-}eq/m^2{\cdot}y$, with m^2 representing square meters of GFA and y a year of a 50-year period. This implied that cases that only reported the NFA, or that were already in $kgCO_2\text{-}eq/m^2{\cdot}y$ but used m^2 NFA as the floor unit or a different reference study period, had to be harmonized to agree with the chosen unit.

The harmonization procedure consisted of two operations: normalization of the reference period and a conversion of floor unit.

The normalization of the GHG emissions for a 50-year period, GHG_{RSP50}, is given by Equation (1), where GHG_0 is the value of the annualized GHG emissions corresponding to a reference study period RSP_0.

$$GHG_{RSP50} = GHG_0 \times \frac{RSP_0}{50} \qquad (1)$$

For the conversion of the GHG emissions from m^2 NFA to m^2 GFA it was necessary to apply a conversion factor, i.e., a constant representing the number of m^2 NFA per m^2 GFA. In the absence of the information needed for its calculation, a constant value of 0.8 was assumed, consonant with the net-to-gross factor chosen by Röck *et al.* (2020b), which is based on a European Commission Directive (European Commission, 2015).

The calculation of the converted GHG emissions, GHG_{GFA}, is given by Equation (2), where GHG_0 is the value of GHG emissions with m^2 NFA as the floor unit and $f_{net-to-gross}$ is the conversion factor.

$$GHG_{GFA} = GHG_0 \times f_{net-to-gross} \qquad (2)$$

If both operations are required, i.e., normalization of the reference period and a conversion of floor unit, then GHG_0 can be substituted in the last expression for GHG_{RSP50}.

Statistical analysis

The final sample comprised a total of 65 cases, of which 44 were reinforced concrete structures and 18 were timber structures. Out of the 18 timber cases, 5 included the effect of CO_2 sequestration in timber and thus were separated from the others to display the influence of this methodological aspect on LCAs' results.

Figure 1 presents the distributions of embodied GHG emissions by type of structural material. In general, the carbon footprint of reinforced concrete buildings was higher, and varied significantly more, than that of timber buildings. To be more precise, the carbon footprint of reinforced concrete buildings ranged between 2.6 and 5.4 $kgCO_2$-eq/m^2.y (1st and 3rd quartile), and had an interval length of 2.7 $kgCO_2$-eq/m^2.y (IQR), while the carbon footprint of timber buildings ranged between 0.7 and 2.0 $kgCO_2$-eq/m^2.y, and had an interval length of 1.3 $kgCO_2$-eq/m^2.y. The inclusion of CO_2 sequestration in the assessment of timber buildings life cycle further increased the distance between the two intervals, ranging between -0.9 and 1.4 $kgCO_2$-eq/m^2.y and measured 2.4 $kgCO_2$-eq/m^2.y in length.

On average, reinforced concrete buildings' material production appeared to release more 2.8 $kgCO_2$-eq/m^2.y than timber buildings' material production. Furthermore, if the benefits of CO_2 sequestration in timber were included, this difference would increase to 3.8 $kgCO_2$-eq/m^2.y. To put into perspective, the average values of the timber subsets, not considering and considering CO_2 sequestration, were, respectively, 1.3 and 0.4 $kgCO_2$-eq/m^2.y. When compared with the average value of the reinforced concrete cases, 4.0 $kgCO_2$-eq/m^2.y, timber structures' material production released on average 69% and 94% less GHG emissions than reinforced concrete structures, respectively.

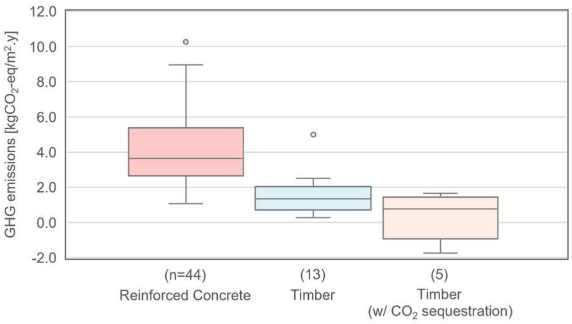

Figure 1. Box plot of the distribution of the embodied GHG emissions in reinforced concrete and timber buildings.

Figure 2 displays the linear regression models between embodied GHG emissions and total number of floors for reinforced concrete buildings and for timber buildings. The models appear to suggest that as reinforced concrete and timber buildings become taller, their carbon footprint increases, however, the rate at which this increase occurs, depends on the structural material used, being faster in reinforced concrete buildings, and more gradual in timber buildings. These upward trends are especially visible in the low values of the subsets: with the increase of the number of storeys the minimum values of GHG emissions also appear to increase. Based on these models, using a timber structural frame instead of a reinforced concrete one might lead to a carbon footprint reduction of at least 2 $kgCO_2$-eq/m^2.y (not considering the effect of biogenic CO_2 sequestration).

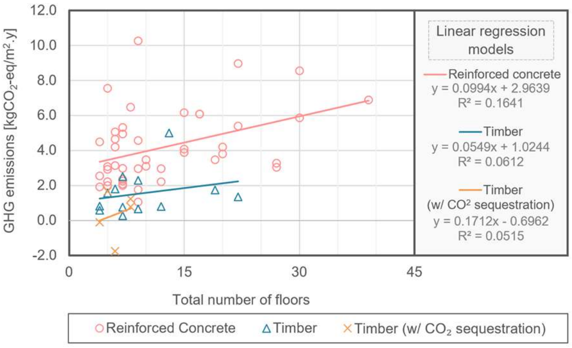

Figure 2. Scatter plot and linear regression models of the embodied GHG emissions as a function of the building height in reinforced concrete and timber buildings.

Based on the linear regression models represented in Figure 3, both reinforced concrete and timber buildings (without CO_2 sequestration) seem to experience a similar increase of their carbon footprint when the mass of structural materials per unit floor area rises, however, at a more slightly gradual rate in timber buildings. When the effect of CO_2 sequestration was accounted for, the trend started at a much lower value (about 3 $kgCO_2$-eq/m^2.y lower) but the rate of the increase remained almost the same. Considering the effect of CO_2 sequestration appears to cause the embodied GHG emissions from material production of structures to be negative until about 750 kg/m^2. Therefore, more than 70% of the variability of the embodied GHG emissions of reinforced concrete and timber structures can be explained by their structural weight (regardless of CO_2 sequestration).

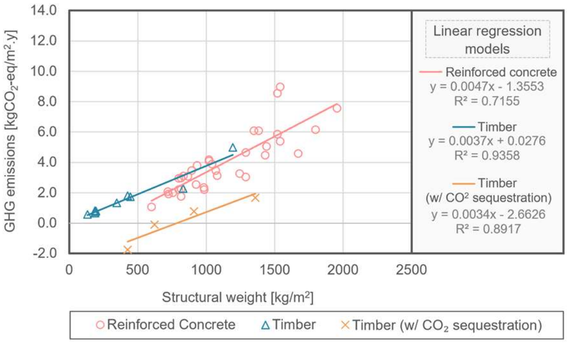

Figure 3. Linear regression models of the embodied GHG emissions as a function of the structural weight in reinforced concrete and timber buildings.

Relatively to the other factors, the findings can be summarized as follows:

- European buildings displayed the lowest carbon footprints;
- Residential and office buildings had very similar embodied GHG emissions and structural weights.
- Input-output LCAs estimated higher values than the majority of the cases assessed with a process-based approach;
- The increase of the percentage of steel did not seem to result in a carbon footprint reduction.

4. BENCHMARKS FOR THE EMBODIED GHG EMISSIONS

One of the key actions that has led to the effective reduction of operational GHG emissions, in the last decades, with a parallel increasing of the relative share of embodied GHG emissions, was the introduction of energy efficiency certificates and legislation (such as the Energy Performance of Buildings Directive in the European Union [European Union, 2010]). But to classify the environmental performance of buildings it is first necessary to have well established benchmarks, which can be defined in one of two ways: through a top-down or bottom-up approach. In a top-down approach, the target values are defined by selecting a global target (budget), distributing it across sectors and sub-sectors, and allocating it at the building level. In a bottom-up approach, the targets are drawn based on the environmental impact of the different building elements.

Benchmark comparison

Due to its simplistic approach, SIA 2040's benchmarks (SIA, 2011), based on the Swiss 2000-Watt Society model, have already been used in some studies as a basis for comparison (Röck *et al.*, 2020b; Hoxha *et al.*, 2016). Its underlying principle is that a reduction on the annual primary energy consumption and annual GHG emissions to 2,000 watts per capita and 1 tCO_2-eq per capita (for all activities in a person's life), respectively, are assumed to be both environmentally sustainable and sufficient to ensure a good quality of life. However, these targets do not comply with the Paris Agreement requirements, the Swiss Energy Efficiency Path, still defines the benchmarks based on an intermediate target of 3,000 watts per capita and 2 tCO_2-eq per capita by 2050 (Kellenberger *et al.*, 2012; SIA, 2011). The GHG emissions benchmarks for buildings in SIA 2040 are derived in a top-down approach, by dividing the carbon budget for 2050 (2 tCO_2-eq) over the different sectors and by further distributing it across the various types of buildings in the sector; in the end, the budget per capita for each type of building is divided by the corresponding energy reference area (ERA) per capita to yield a carbon budget per unit floor area (Kellenberger *et al.*, 2012; SIA, 2011).

In order to successfully mitigate embodied GHG emissions of structural frames and comply with carbon budgets, the values of the cases of the meta-analysis' sample were compared to a variation of the Swiss benchmarks. These adapted benchmarks were based on the more ambitious goal of reaching the original 2000-Watt Society target of 1 tCO_2-eq per capita by 2050, and therefore required the division of the values defined in SIA 2040 by a factor of two; in addition, since the unit floor area of the original benchmarks was m^2 ERA, a conversion factor of 0.9, based on the GFA-to-ERA ratio used in SIA 2040 (Jakob *et al.*, 2016), was also applied. The adapted benchmarks per m^2 GFA, derived from the 2050 target of 1 tCO_2-eq per capita, are given by Equation (2).

$$Budget_{1\ tCO_2-eq} = \frac{Budget_{SIA\ 2040}}{2} \times f_{ERA-GFA} \quad (3)$$

Figure 4 displays the embodied GHG emissions of buildings' structural frames and the respective benchmarks of each type of building. As can be noticed, while a significant number of reinforced concrete buildings did not meet the benchmark for the embodied emissions, only one of the timber buildings stood above the target value for embodied emissions. Furthermore, for the most part, the reinforced concrete buildings that did meet the benchmark had a low quantity of emissions left for the other components of the buildings, less than 2 $kgCO_2$-eq/m^2.y. Timber buildings, on the other hand, had a reasonable embodied emissions surplus, between 2.6 and 3.7 $kgCO_2$-eq/m^2.y., if the effect of CO_2 sequestration wasn't or was included, respectively. In some of the timber buildings in which the effect of CO_2 sequestration was accounted for, there was even a negative carbon footprint of the structural system.

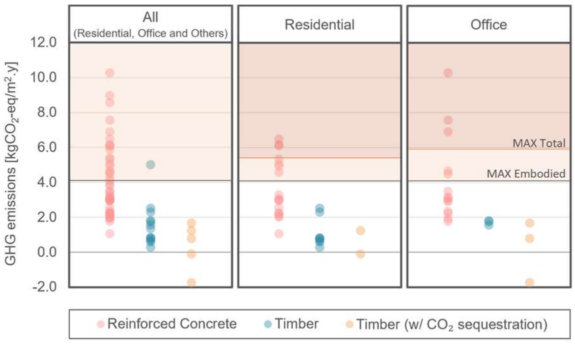

Figure 4. Structural frames' embodied GHG emissions benchmark comparison.

As Figure 5 shows, for some of the buildings, opting for a timber design, instead of reinforced concrete, made the difference between meeting or not meeting the target value for embodied emissions. The difference between choosing a reinforced concrete design or a timber design, regarding the remaining emissions budget, was, on average, 2 $kgCO_2$-eq/m^2.y, yet with the inclusion CO_2 sequestration it increased to 5 $kgCO_2$-eq/m^2.y.

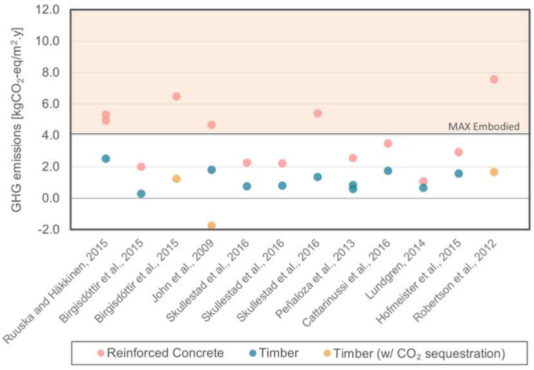

Figure 5. Benchmark comparison of the two design alternatives (reinforced concrete and timber) for the same building.

Reference and target values definition

Using the meta-analysis data set, reference and target values for reinforced concrete and timber structures (including substructure and superstructure) were defined, assessing the carbon footprint of buildings' structures more deeply and making these values available for comparison. The approximate models were defined by fitting distributions to the data, using the R programming language (R Development Core Team, 2013) with the *fitdistrplus* package (Delignette-Muller and Dutang, 2022), and following the method described by Delignette-Muller and Dutang (2015).

Initially, the distributions were selected from a group of candidates that were chosen by observing the empirical plots of the data; since the empirical distributions (of the reinforced concrete sample and timber sample) were positively skewed, the gamma, lognormal and Weibull distributions were considered. With the distributions chosen, the values of the parameters were estimated with the maximum likelihood estimate method to generate the distributions that best fit the data. Then, the goodness-of-fit of the distributions was evaluated by a visual assessment that consisted in comparing, for each sample, the theoretical probability density functions (PDFs) to the empirical histogram and the theoretical cumulative distribution functions (CDFs) to the empirical one; it also included the analysis of the quantile-quantile (Q-Q) plot and probability-probability (P-P) plot. In addition to the visual assessment, a statistical assessment was also performed, by comparing goodness-of-fit statistics, namely the Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling statistics, between the candidate distribution.

Based on the visual assessment, the distribution that looked the most compatible with the data was the log-normal distribution, for both reinforced concrete buildings and timber buildings, as represented in Figure 6.

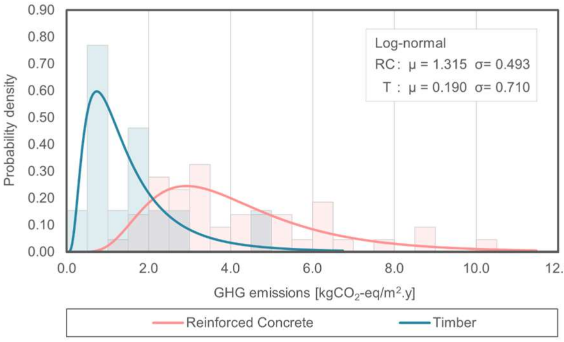

Figure 6. Empirical histograms and fitted log-normal distributions of reinforced concrete buildings and timber buildings.

Table 1 presents the theoretical reference and target values for reinforced concrete structures and for timber structures.

Table 1. Theoretical and empirical reference and target values for reinforced concrete structures and timber structures.

Structure	GHG emissions (kgCO2-eq/m2.y)	
	Reference value	Target value
Reinforced concrete	**3.7**	**1.7**
Timber	**1.2**	**0.4**

The visible difference between the reinforced concrete values and the timber values is considerable: the reference and target values are more than three times higher for reinforced concrete buildings than they are for timber buildings. Moreover, although reinforced concrete buildings have a larger margin for improvement, timber buildings' reference value is still lower than the target for reinforced concrete buildings. If the current target value for the structural system is successfully met, the available embodied budget for the other building components and life cycle stages is about 60% for reinforced concrete buildings and 90% for timber buildings. If it is not, and values are kept at a reference level, then the remaining budget becomes limited to about 10% for reinforced concrete buildings and to 70% for timber buildings.

Labelling system suggestion

In addition to assessing the embodied GHG emissions of buildings from the early stages of the building design, it would be important that, in parallel to the energy efficiency certification, a classification of the embodied GHG emissions is also developed and adopted. It seems that a common classification system, created with a top-down approach, so that climate targets are considered, would be more beneficial — but it is important that the distributions of embodied GHG emissions values for the different types of structures are also taken into account in order to ensure its practicality.

Therefore, a 'carbon' labelling system was designed to classify the environmental performance, in terms of climate change impact, of buildings' structures. This label is based on the new European energy label (European Comission, 2021b) and is divided into seven classes, from best to worst performance:

- A, the structure takes less than 15% of the embodied budget;
- B, the structure takes between 15% and 25% of the embodied budget;
- C, the structure takes between 26% and 50% of the embodied budget;
- D, the structure takes between 51% and 75% of the embodied budget;
- E, the structure takes more than 75% of the embodied budget;
- F, the structure takes the entire embodied budget or exceeds it by 50% or less;
- G, the structure exceeds the embodied budget by more than 50%.

These percentage boundaries were defined by taking into consideration the values that can be achieved by (reinforced concrete and timber) buildings. The actual class boundaries (in kgCO$_2$-eq/m^2.y) can be found in Figure 7, where the suggested 'carbon' label is represented.

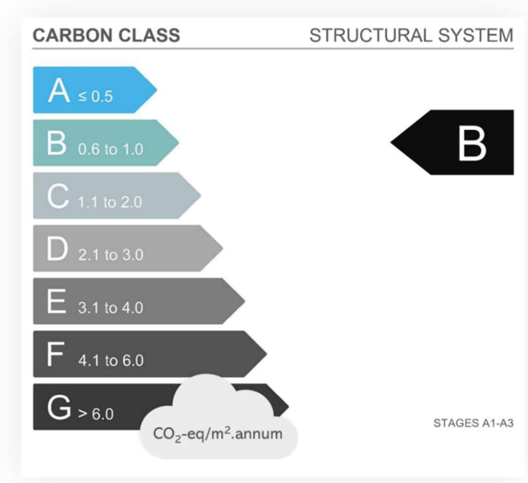

Figure 7. Example of the suggested carbon label for a building's structure classified with a B.

5. DISCUSSION AND CONCLUSIONS

Discussion

Based on the meta-analysis results, the embodied GHG emissions of buildings attributed to the manufacture of structural materials range between 2.6 and 5.4 kgCO$_2$-eq/m^2.y in reinforced concrete buildings and 0.7 and 2.0 kgCO$_2$-eq/m^2.y in timber buildings (or -0.9 and 1.4 kgCO$_2$-eq/m^2.y if the sequestration of biogenic CO$_2$ is included). Compared to the values presented in Section 2, these figures are quite smaller than those of Simonen *et al*. (2017) and De Wolf *et al*. (2015) but are relatively similar to those calculated by Hart *et al*. (2021) for superstructures, with the difference that their upper values were somewhat lower. The value discrepancy between this study's results and those of Simonen *et al*. can be attributed to the inclusion of the construction stage (A4-A5) in their analysis, however, for the results of De Wolf *et al*., no explanation was found, yet interestingly, despite the difference in embodied GHG emissions, the structural weight values were fairly similar. The weight of structural materials per unit floor area in this study varies between 821 and 1,374 kg/m^2 in reinforced concrete buildings and 190 and 872 kg/m^2 in timber buildings. The only significant difference that can be noted between these values and those of De Wolf *et al*. lies in the upper values of timber buildings. The contrast between the two is most likely a consequence of the samples having cases with distinct characteristics (namely the number of basements and material of the building internal core).

The exploration of the influence of different factors on the carbon footprint of structures in the meta-analysis indicated that, at a large scale (i.e., comparing different buildings from different contexts), there is too much unexplained variability to identify a clear positive correlation of the embodied GHG emissions with the building height. However, a number of studies have provided evidence that increasing the number of storeys of a building leads to an increase of the embodied GHG emissions — due to the required increase of volume of the vertical elements, to resist gravity loads, and the effect of larger lateral loads (caused by wind) (Hart *et al*., 2021; Luo *et al*., 2016; Nadoushani and Akbarnezhad, 2015a; Skullestad *et al*., 2016).

Overall, the factor that appears to have the strongest relationship with the embodied GHG emissions of structures is the structural weight — as could already be expected, given that GHG emissions are calculated by multiplying an emission factor to a mass or volume of material. As the mass of structural materials per unit floor area rises, the carbon footprints of reinforced concrete and timber structures also increase — at a similar rate and with similar embodied GHG emissions for the same structural weight.

For the same total number of storeys, most timber cases had lower structural weights than the reinforced concrete ones, which resulted in them also having lower embodied GHG emissions. Yet, the existence of reinforced concrete lift/staircase cores, shear walls (to provide further stability) or basements led some cases to have identical values to those of reinforced concrete frames.

As for the influence of the other factors on the embodied emissions of reinforced concrete structures, the findings can be summarised as follows: European buildings displayed the lowest carbon footprints; residential and office buildings had very similar embodied GHG emissions and structural weights, but the latter varied more in buildings with a residential use; input-output LCAs estimated higher values than the majority of the cases assessed with a process-based approach; and the increase of the percentage of steel did not seem to result in a carbon footprint reduction. It should be noted, however, that some of the subsets created to analyse these factors (namely the geographic location, building use and LCA approach) need more observations to provide solid evidence.

The comparison of the cases to a variation of the Swiss SIA 2040 benchmark, that was based on a annual carbon budget of 1 tCO_2-eq per capita by 2050, displayed that, in the cases where the benchmark is not exceeded, reinforced concrete structures leave a very limited quantity of emissions left for the other components and life stages of the building. On the other hand, timber buildings left in general a reasonable surplus of embodied emissions, for the most part more than half of the budget; for some of the cases that considered CO_2 sequestration, the surplus was even higher than the initial budget, due to a negative carbon footprint. It was also shown that using a timber structure instead of a reinforced concrete one, in some instances, can make the difference between meeting and not meeting the benchmark for embodied emissions; and if the reinforced concrete design already meets the benchmark, it can increase the available budget for other building elements. The average difference between reinforced concrete and timber designs was 2.0 and 5.8 $kgCO_2$-eq/m^2.y if the benefit of CO_2 sequestration is not considered and if it is, respectively — the regression models of the embodied GHG emissions with the total number of storeys in Section 3 (Figure 5) also suggested the former value for timber buildings that did not include CO_2 sequestration.

The defined reference and target values for reinforced concrete and timber structures indicate that minimizing the carbon footprint of timber buildings is more beneficial than focusing on trying to optimize the reinforced concrete design to reduce its impact. The reference and target values were 3.7 and 1.7 $kgCO_2$-eq/m^2.y for reinforced concrete structures, more than three time higher than the timber structures values, 1.2 and 0.4 $kgCO_2$-eq/m^2.y. Even if efforts are made and the embodied emissions of a reinforced concrete structure are successfully reduced to the target level, a timber structure with an average performance will still have a lower carbon footprint. If embodied emissions of structures are kept at reference level, reinforced concrete and timber buildings will have 10% and 70% of the budget available for other building components and life cycle stages, respectively. Yet if they are minimized to the target level, these figures increase to 60% and 90%, respectively, for reinforced concrete and timber buildings.

While establishing reference and target values enables building designers to assess the performance of a specific structural system (in this case reinforced concrete or timber) during the building design, the implementation of a labelling system, such as the one suggested, would facilitate the comparison of the environmental performance (in terms of GWP) of different systems, given that it is not specific and is based on a top-down budget. Furthermore, it would be better way of informing ordinary people that are not familiarized with LCA terminology about the carbon footprint of their houses or workplaces, which as a result could increase the demand for low carbon buildings.

Conclusion

In order to reach the ultimate goal of net-zero emissions by 2050 and consequently limit global warming to 1.5ºC, life cycle emissions need to be brought down to net-zero too — including embodied emissions. The monitorization and regulation of this emissions must therefore become a priority, together with increasing buildings' energy-efficiency. Architects and structural engineers have a major role in this path toward carbon zero, as during the design, they have the power to compare and minimize different alternatives. With this in mind, this study investigated the influence of different factors on the embodied GHG emissions of structures, and established reference and target values to be considered during the design of reinforced concrete and timber structural systems. The analysis indicated that the main driving factor of embodied emissions of structures is the structural weight (i.e., the mass of structural materials per unit floor area). If the buildings' structures are optimized from a material efficiency perspective to reduce the quantities of structural materials, then their GWP will too be minimized. However, as the reference and target values indicated, at present, even if reinforced concrete structures' carbon footprints are reduced to the target value, timber structures with average performances will still have lower embodied GHG emissions. Furthermore, when compared to the variation of the Swiss SIA 2040 benchmark, reinforced concrete structures at target level continued to consume most of the budget for embodied emissions, leaving only 40% of the budget for the remaining life cycle stages and building components. It should be note, however, that a timber design might not be the optimal solution in all scenarios. Distance from suppliers, available modes of transportation and end-of-life options are some of the important aspects that should be considered (Cattarinussi & al. 2016; Hart & al. 2021).

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