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

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

De modo a alcançar os objetivos acordados no Acordo de Paris e limitar o aquecimento global a 1.5ºC, é necessário que as emissões líquidas de gases com efeito estufa (GEE) sejam limitadas a zero até 2050. A monitorização e regulamentação das emissões produzidas ao longo do ciclo de vida constituirá um passo importante nesse sentido, particularmente das que são consideradas incorporadas. O presente estudo tem por objetivo investigar a influência de diferentes fatores nas emissões incorporadas de GEE provenientes da produção dos materiais utilizados nas estruturas de betão armado e nas estruturas de madeira de altura média e de altura elevada, através de uma meta-análise com 62 casos, e estabelecer valores de referência e valores alvo para as mesmas. Os resultados identificam o peso estrutural dos edifícios como o fator determinante para as emissões incorporadas. O aferimento do desempenho dos casos com os valores alvo estabelecidos na SIA 2040 revelou ainda que a produção dos materiais das estruturas de betão armado consome a maior parte do valor disponível para as emissões incorporadas. Optar por uma estrutura em madeira pode aumentar o valor de emissões incorporadas disponíveis para os restantes elementos do edifício e etapas do ciclo de vida e, em alguns casos, pode fazer a diferença entre atingir e não atingir o valor estabelecido para as mesmas. Com base nos percentis 50 e 5 de distribuições ajustadas, os valores de referência e valores alvo são, respetivamente, 3.7 e 1.7 $kgCO_2$-eq/m^2.a para as estruturas de betão armado e 1.2 e 0.4 $kgCO_2$-eq/m^2.a para as estruturas de madeira. Adicionalmente, foi também demonstrado que a criação e introdução de uma etiqueta de ‘carbono’ seria uma medida que permitiria informar de um modo claro o impacto ambiental dos edifícios, em termos de Potencial de Aquecimento Global.

Palavra-chave: Avaliação de ciclo de vida (ACV); Betão armado; Carbono incorporado; Construção; Edifícios; Emissões de gases com efeito de estufa (GEE); Impactes ambientais; Madeira; Valores de referência

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

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Glossary

CDF Cumulative Distribution Function.

CLT Cross-Laminated Timber.

EWP Engineered Wood Product.

GFA Gross Floor Area.

GHG Greenhouse Gas.

GWP Global Warming Potential.

LCA Life Cycle Assessment.

LCI Life Cycle Inventory.

LVL Laminated Veneer Lumber.

NFA Net Floor Area.

PDF Probability Density Function

RC Reinforced Concrete

SIA Swiss Society of Engineers and Architects

SLR Systematic Literature Review.

Chapter 1

Introduction

Human activity is very likely the main cause of global warming; with anthropogenic greenhouse gas emissions (GHG) currently 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 stated "*the need for an effective and progressive response to the urgent threat of climate change*". As a result, the Parties 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). At that time, knowledge surrounding the effects that a 1.5 ºC global warming would have on climate-related risks and the available pathways was limited (IPCC, 2018). 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 in 2018 on the impacts of global warming of 1.5 ºC above pre-industrial levels and related global greenhouse gas emission pathways*" (UNFCCC, 2015). The emission reduction pathways therein, showed that a "*rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems*" (IPCC, 2018) would be needed; these transitions would require deep emissions reductions across all sectors. To establish clear targets that stay consistent with these required emissions reductions, a carbon budget that relates cumulative carbon dioxide (CO_2) emissions to global mean temperature increase can be defined (IPCC, 2018). Through distribution of the residual carbon budget along the remaining years until carbon neutrality is reached, 2050 and 2070 for 1.5 ºC and 2 ºC global warming limit respectively (IPCC, 2018), an annual carbon budget can be quantified and subsequently allocated to each sector.

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 and related emissions, yet embodied emissions have remained unchanged. This reduction in operational energy has led to a decrease in buildings full life cycle emissions and to an increase in embodied emissions' relative share. Moreover, buildings classified as passive houses or nearly zero energy buildings have also shown to have an increase in the absolute contribution of embodied GHG emissions (Röck *et al*., 2020a). When the full life cycle of these high energy-efficient buildings is analysed on a timescale, embodied emissions become even more prominent, since the initial 'carbon spike' originated from building production overshadows operational GHG emissions during the first 35 years, in other words, the timeframe for climate change mitigation is governed by the embodied emissions (Röck *et al*., 2020b). In light of these evidence, it becomes clear that to further reduce buildings sector's impact on climate, attention must shift from an operational efficiency perspective to a holistic life cycle approach. The reduction of buildings embodied emissions can be achieved by replacing materials with high carbon footprints with less carbon-intensive materials; IPCC fifth assessment report suggests substituting concrete and steel in buildings construction with timber (IPCC, 2014a).

1.1 Motivation

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, which when compared with today's 56% (2020) (United Nations - Department of Economic and Social Affairs - Population Division, 2018) results in an absolute growth of 2.2 billion inhabitants. Accompanying this rise in urban population comes a new challenge, guaranteeing housing for all whilst simultaneously limiting anthropogenic GHG emissions to meet the global mean temperature increase target of 1.5 ºC. 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), that if not addressed properly could lead to the commitments made on the Paris Agreement not being delivered, due to the considerable spike of GHG emissions emerging from building production. Monitoring and regulating buildings embodied emissions through legislation has thus become a significant step in minimizing buildings sector contribution to climate change. 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). 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 provides building designers with a direction to follow. Although these values do not cover the whole life cycle, if the impact from material production, that tends to be quite significant in relative terms (Hart *et al*., 2021), is reduced to a minimum, then the whole GWP will too be minimized. In addition, if architects and structural engineers know which factors influence the carbon footprint of structures and how they do it, they will have a better sense of how to optimise the design of the building to reduce its impact.

1.2 Objectives

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

- 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?
- 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?
- How can timber structures assist designers in meeting embodied GHG emissions budgets?

Initially, a sample of reinforced concrete and timber cases will be collected from literature based on a systematic literature review and, after extracting and harmonizing their data, 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 GWP and provide a clear way of comparing different systems.

Finally, the results will be discussed and compared to other studies' results.

1.3 Document structure

This document consists of five Chapters: Introduction, Background, Meta-analysis: Embodied GHG Emissions and Structural Weights, Benchmarks for the Embodied GHG Emissions, and Discussion and Conclusions.

Chapter 1 introduces the climate crises, the growing significance of embodied emissions in buildings' total carbon footprint and outlines the study's motivation and methodology.

Chapter 2 provides the background of the current political context in terms of embodied emissions regulation and state of knowledge of embodied GHG emissions of structures, presents the origin of the embodied emissions of reinforced concrete buildings, introduces timber construction, and describes the Life Cycle Assessment methodology.

Chapter 3 details the methodology of the meta-analysis, identifies the range of values of embodied GHG emissions and structural weight of reinforce concrete buildings and investigates the factors that influence the embodied GHG emissions of structures.

Chapter 4 compares the carbon footprint of the cases from the meta-analysis to a top-down benchmark for embodied GHG emissions, defines reference and target values for reinforced concrete and timber buildings' structures, discusses the differences between using reinforced concrete and timber structures in complying with carbon budgets and proposes a labelling system for embodied GHG emissions of structures.

Chapter 5 discusses the results, while comparing them to other studies' findings, and presents the conclusions and the paths that can be explored in future works.

Additionally, Appendix A provides supplementary materials, such as, more comprehensive tables and additional charts and figures, and Appendix B presents the data of the collected cases.

Chapter 2

Background

The past endeavors to improve building's energy-efficiency have successfully lowered operational energy consumption (i.e., the energy used for heating, cooling, lighting, etc.) and subsequent emissions, however, 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). Energy-efficiency improvements, such as reducing the building's thermal transmittance, often require the introduction of additional materials (e.g., insulation) or the use of more energy intensive ones (e.g., better performing windows) in the building thermal envelope, which can amount to a greater share of embodied emissions (Röck *et al.*, 2020b; Sartori and Hestnes, 2007; Ruuska and Häkkinen, 2015); in buildings following current energy standards, embodied GHG emissions account on average for almost 25% of the life cycle emissions, however, in highly energy-efficient buildings this number is close to 50% — and in extreme cases surpasses 90% (Röck *et al.*, 2020b). To further enhance buildings' environmental performance, embodied emissions must be assessed from the early stages of the design process, particularly, during the structural system conception, as it can be one of the main contributors to the climate change impact of buildings (Dokka *et al.*, 2013; Kaethner and Burridge, 2012; Wallhagen *et al.*, 2011; De Wolf, 2014). To that end, reference and target values need to be specified.

At regulatory level, minimum standards should be established for buildings' Global Warming Potential (GWP), as they were for the energy performance (European Union, 2010; Frischknecht *et al.*, 2019). In addition, recognising the important role that Energy Performance Certificates (EPC) can have in informing and influencing stakeholders (e.g., investors, builders, owners, occupiers and promoters) during the decision-making process, favouring energy-efficient buildings and consequently increasing their market demand (BPIE, 2014), the certification of the GWP of buildings would also constitute a valuable step in the path towards net zero GHG emissions by 2050 (as required to limit global-warming to about 1.5ºC [IPCC *et al.*, 2018]).

In Europe, some countries have already started taking action towards this direction by introducing regulation on life cycle emissions and implementing benchmarking systems (i.e., systems that enable the environmental performance of buildings to be evaluated by comparing it to reference values) (Frischknecht *et al.*, 2019; Trigaux *et al.*, 2021; BPIE, 2021). The United Kingdom, Germany and Switzerland have adopted the compulsory life cycle assessment of public buildings. The Netherlands, since 2017, obliges the assessment of embodied GHG emissions, and since 2018, restricts the impact of buildings considering several impact categories, including GWP. France already has in place a regulation establishing a limit on the embodied GHG emissions of buildings, that progressively decreases every three years from 2022 to 2031. Denmark will introduce a cap on whole life cycle emissions by 2023 that will also gradually decrease, but every two years until 2029. Likewise, Finland and Sweden plan to have a ceiling on the GHG emissions of buildings' full life cycle set by 2025 and 2027, respectively.

Within the European Union, a major revision of the Energy Performance of Buildings Directive, adopted by the European Comission at the end of 2021, has just introduced what might be one of the most significant measures related to the regulation of embodied GHG emissions taken to date at a large scale: the mandatory assessment of new buildings' GWP. From 2030, Member States have to ensure that the life cycle GHG emissions of new buildings are assessed and communicated (in $kgCO_2$-eq/m^2.y of a reference study period of 50 years) through the building's EPC (European Comission, 2021a).

2.1 Previous work

In order for architects and structural engineers to improve the design of buildings, from a climate change impact mitigation perspective, or for buildings' carbon footprint to be regulated, it is necessary that the ranges of values of embodied GHG emissions are known. Previous studies have already built up a considerable body of knowledge around the carbon footprint of structures. Simonen *et al.* (2017) compiled a database with data from literature and private and publicly accessible datasets. In their analysis, embodied emissions from the extraction and manufacture of materials (known as material production or product stage) were assessed by building use, buildings scope and number of storeys. 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 (1^{st} and 3^{rd} quartiles 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 values were analysed by building use, structural system, building area, number of storeys and Leadership in Energy and Environmental Design (LEED) certification. 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 (1^{st} and 3^{rd} quartiles for a reference study period of 50 years).

With the aim of thoroughly investigating the GWP difference between structural systems, Hart *et al*. (2021) systematically compared the total life cycle embodied GHG emissions of steel, reinforced concrete and timber superstructures, by assessing more than a hundred frame configurations (from 2 to 19 storeys) of each structural system. The results showed that the emissions from material production account for most of the GWP 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 (1st and 3rd quartiles for a reference study period of 50 years). However, emissions from other stages (especially those stemming from the 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. It was also demonstrated that the design optimization plays an important role in reducing structures' carbon footprint. One of the aspects of building design that appeared to have an influence over the impact of structures was the building height. In the three structural systems, the increase of the number of storeys was accompanied by an increase of embodied GHG emissions (due to the structural weight increase caused by the wider columns at lower levels), however, in timber structures, due to the lower mass of the elements, the rate of this increase was lower. In general, the factors that were present in buildings with a low GWP were larger floor areas, fewer storeys (below five for reinforced concrete buildings and below eight for timber and steel buildings), longer beams, and lower floor and envelope loads.

In recent years, various studies have explored the difference between using a timber or reinforced concrete frame on the carbon footprint of buildings. 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 structure and a timber structure. The study comprised several different scenarios, with distinct calculation approaches and technological assumptions, and 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%. Furthermore, when the substitution of fossil fuels with biomass from deconstruction waste was accounted, the climate change impact became negative, indicating that the use of timber in the building structure would surprisingly result in an overall avoidance of emissions. The analysis of the climate change impact as a height function showed that buildings taller than 12 storeys (known as high-rise), regardless of the structural material, have a height premium, i.e., the increasing height leads to an increase in structural material per gross floor area, due to the action of more substantial lateral loads, which as a consequence raises the emissions per gross floor area. However, the timber structures presented a much less prominent upward trend, causing high-rise buildings GHG emissions saving potentials to increase significantly with height and surpass low- and mid-rise buildings emissions reductions — this is in line with the findings of Hart *et al*. (2021). Eliassen *et al.* (2019) assessed the life cycle environmental impact of two identical mid-rise buildings located side by side but with different above-ground structural systems, one with a conventional reinforced concrete structure and the other with a timber structure consisting of CLT load-bearing walls and floors. The two buildings were joined by an underground parking garage made of reinforced concrete. The findings showed that during the production stage the timber building had 25% lower GHG emissions than the reinforced concrete building, yet if the contribution of the common underground parking garage were to be set aside this reduction would escalate to 36%. When the assessed life cycle was broadened to also include transport and operational energy of the whole building the emissions savings dropped to 13%. Cattarinussi *et al*.

(2016) compared two identical high-rise buildings (17 storeys above ground and 2 basements) designed with different structural systems, one 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). The foundations of the two systems were also different 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. The study also displayed the importance of using rail instead of road transport over long distances.

However, research has shown that a reduction in embodied GHG emissions does not have to come necessarily from a change of structural system. Nadoushani and Akbarnezhad (2015a; 2015b) examined the GWP of different structural designs of reinforced concrete buildings (moment resisting and shear wall frames with 3, 10, 15 and 20 storeys), and the results showed that the embodied GHG emissions decreased, in all four versions, from a moment resisting frame to a shear wall frame design. In addition, it was also observed that the increase of the building height led to an increase of the GWP of the frames.

2.2 Reinforced concrete

Reinforced concrete is a composite material that combines concrete's compressive strength with steel's tensile strength and ductility. Though the concept of embedding steel in concrete to improve its mechanical properties is somewhat recent (dating from the middle of the 19th century), concrete in itself has been used for centuries. Today, concrete is the second most consumed substance on the planet in terms of annual volume after water (IEA, 2009); its widespread use in modern-day construction is partly due to the outstanding longevity and structural performance that it offers. Concrete's formulation flexibility allows designers to optimize its properties for specific settings, making it exceptionally versatile when compared to other materials. For quite a while, these appealing qualities and its wide availability outshined the environmental burdens that come with its production, more specifically during Portland cement manufacturing. Cement manufacturing accounts for 7% of all anthropogenic CO_2 emissions, more than one-half of which are process-based emissions, due to clinker production, and the remaining are direct emissions, caused by fossil fuel combustion and resulting primarily from pyro-processing, the process in which materials are heated to high temperatures in a kiln to trigger physical and chemical reactions (including the calcination of limestone) (IEA, 2018; Czigler *et al.*, 2020).

Clinker production requires a process known as limestone calcination, which removes CO_2 from calcium carbonate ($CaCO_3$) and yields calcium oxide (CaO), known as lime. Throughout the structure's service life, part of the emitted CO_2 is reabsorbed into the concrete in a chemical reaction termed carbonation: the hydration products, mainly calcium hydroxide ($Ca(OH)_2$), existing in the cement paste react with the atmospheric CO_2 and produces $CaCO_3$, reversing the calcination process. This reaction occurs from the outside inwards as the CO_2 is diffused in the pore structure, and is dependent on the exposure conditions, the composition of the paste, and the available surface for absorption. In buildings, due to the limited specific surface area of the structural elements, carbonation occurs at a slow rate and cannot offset the bulk of the calcination emissions. Studies (Pade and Guimaraes, 2007) have shown that at the end of buildings' service life, up to a third of the CO_2 emitted during the calcination process is rebound to the cement paste through carbonation. Additionally, if the concrete is crushed after demolition, during the recycling process, and is left exposed for a period of time (from 2 weeks to 4 months), the net CO_2 emissions can be more than halved in some cases. However, the variability of these numbers is very high, since they are influenced by a number of methodological assumptions and physical factors, not to mention, carbonation has an undesirable effect on reinforced concrete's durability, due to the depassivation of the reinforcing steel and subsequent corrosion, and is in many cases hindered with surface treatments, which ultimately reduce the CO_2 uptake. The only way to avoid the CO_2 released during the calcination process is to minimize clinker production, by either substituting it with industrial by-products, such as silica fume, fly ash, and blast furnace slag, or with recycled cement (Meyer, 2009). As for the direct emissions, a similar co-processing attitude can be taken towards substituting fossil fuels with biomass from waste along with energy-efficiency improvements (WBCSD, 2014). Despite the efforts made in the second decade of the 21st century to lower the cement industry's carbon footprint, a significant portion of the planned decarbonization is still relying on carbon capture and storage (CCS) technology which is still in its infancy.

The iron and steel sector accounts for 10% of global CO_2 emissions arising from fossil fuel combustion and industrial processes (IEA, 2020). Over 50% of the global demand of steel is created by the construction sector, and about a fifth of it can be attributed to the use of reinforcing steel in buildings (Moynihan and Allwood, 2012; Assunção *et al*., 2022). Steel can be produced either by converting iron ore into virgin steel or by recycling steel scrap. The conventional method for producing virgin steel involves chemically reducing the iron ore into crude iron, in a blast furnace, and subsequently refining it into crude steel in a basic oxygen furnace. About 70% of the emissions stemming from the production of steel through this method are attributed to the conversion of iron ore into crude iron in the blast furnace (De Beer *et al*., 2000; Wang *et al*., 2009). This process requires heat to be generated, often through the combustion of coal, and the presence of coke (a coal product) as the primary reducing agent — this is the reason why the steel sector is responsible for about 15% of the global consumption of coal (World Steel Association, 2016). Alternatively, scrap-based steel production is carried out in an electric arc furnace that runs on electricity (instead of coal), and only requires an eight of the energy used to produce virgin steel. Due to the continuously rising demand for steel and the use of scrap in basic oxygen furnaces (in virgin steel production), recycled steel has not yet been able to completely fulfil the need for steel. Only around 30% of the global steel production is currently being supplied by recycled material (IEA, 2020). As long as demand keeps on growing, virgin steel will need to continue being produced. Based on forecasts, global steel demand is expected to increase by more than a third until 2050, yet to meet climate targets, the sector's emissions will have to be at least halved by that date (and continue to decrease afterwards until the target of net-zero emissions is achieved, preferably by 2070) (IEA, 2020). There are several ways of reducing the environmental impact of the steel industry on the climate: by improving material and process efficiency; increasing the availability of steel scrap and the share of scrap-based production and using renewable sources of electricity to power the electric arc furnaces; electrifying the processes that generate heat (and currently require fossil-fuels); and employing innovative technologies such as hydrogen-based direct reduction (that use hydrogen as the reductant instead of coking coal) and carbon capture, use and storage (Hoffmann *et al.*, 2020; IEA, 2020). However, similar to concrete, a considerable portion of the necessary carbon emission reduction for complying with the goal of net-zero emissions by 2050 requires technology that is still in development and is not yet technically or economically viable (IEA, 2020). Alternative materials, such as timber, could relieve the decarbonization process of cement and steel by taking a share of their demand (Assunção *et al.*, 2022; Czigler *et al.*, 2020).

2.3 Timber

Historically, European dwellings were mostly constructed with masonry, and more recently, with concrete and steel. Apart from Scandinavia and some regions of western and central Europe, namely the United Kingdom, Northern France, Germany, Austria, and Switzerland, where traditional houses were built with timber (e.g., in half-timbered buildings), timber has been solely used as a secondary component (e.g., timber floors in masonry buildings) or as a reinforcement against seismic action for the main structure (e.g., internal timber frames in masonry buildings known as "*Pombalina cage*"). However, the current climate situation and the forthcoming embodied carbon regulations are forcing the buildings industry to look for new solutions that minimize buildings' carbon footprint.

Timber construction is generally perceived as being more sustainable than concrete and steel (Petruch and Walcher, 2021) due to its natural origin and renewability. Apart from being a biotic material, i.e., stemming from a living organism, timber also functions as a carbon sink during its growing phase, as it stores carbon that was absorbed from the atmosphere resulting from the photosynthesis process. As a structural material, in general, it can create three types of building structural systems: light wood-frame, post-and-beam, and mass timber. Light wood-frame, or stick frame, is commonly employed in low-rise buildings and consists of several closely spaced solid timber studs and joists nailed together forming a light wood skeleton that distributes the load through the framed walls and floors. Post-and-beam, or timber frame, also used in low-rise construction, can be differentiated from light wood-frame by the thicker, less numbered, and more spaced timber elements that function as load-bearing columns, beams, and trusses, as illustrated in Figure *1*. Mass timber, the most recent timber system, uses engineered wood products (EWP) as columns, beams, and load-bearing walls and floors. Its recent appearance in city skylines, namely in mid- and high-rise buildings, has been attracting a great deal of attention to this new way of constructing.

Figure 1. Examples of a light wood-frame (left) and a post-and-beam timber frame (right).

2.1.1 **Impact on forests**

Despite being regarded as a sustainable material, the idea of cutting down a tree still prevails as something negative (Petruch and Walcher, 2021), and while natural heritage must be preserved, non-protected areas should be managed to maintain productivity. As a forest reaches maturity, its biospheric carbon sink becomes saturated and hinders its capacity to remove CO_2 from the atmosphere (Nabuurs *et al*., 2013). On the other side, sustainably managed forests can provide substitute products of carbon-intensive mineral-based materials and fossil fuels, that would otherwise be produced and consumed (Gustavsson *et al*., 2017). This can be accounted as a climate benefit, since the non-production of these products results in avoided anthropogenic GHG emissions.

2.1.2 **Biogenic carbon**

Biogenic carbon comprehends the carbon that is absorbed, sequestered, and emitted to the atmosphere by biomass. During trees growth, small pores present on leaves surface absorb CO_2 from the atmosphere and proteins held in leaf cells capture light energy for the photosynthesis process. In this process, the absorbed CO_2 is converted into carbohydrates that can be stored in the plant's tissues forming the biomass. When the biomass decomposes or is incinerated, either by natural disturbances or biofuel combustion, the stored carbon is released back to the atmosphere, closing the biogenic carbon cycle.

Biogenic carbon emissions are often assumed as climate neutral because their release is balanced out by the CO_2 absorbed during biomass regrowth, resulting in a net zero carbon flux (Cherubini *et al*., 2011). Although this can be true in the long term, temporary unbalances due to variations in the biospheric carbon pool may cause a positive or negative delta in the atmospheric concentration of CO_2. Depending on the earth's concentration of atmospheric CO_2, it can either experience a temperature increase or decrease, i.e., a positive variation of the CO_2 content in the atmosphere can cause a positive radiative forcing which leads to more sun's energy being trapped by the CO_2 particles and consequently a warming effect, conversely, a negative variation can result in a negative radiative forcing, leading to more energy being radiated back to space and thus creating a cooling effect. Extending the lifetime of biomass further than trees rotational period with long-lasting products, such as EWP in buildings' structures, enables the atmospheric levels of CO_2 to drop, by postponing the release of the biogenic emissions. However, the significance of such benefits to climate change mitigation is questionable (Kirschbaum, 2006; Levasseur *et al*., 2012).

2.1.3 **Engineered wood products**

Constructing with bio-based materials, such as engineered timber, can transform cities' building stock into dense carbon pools (Churkina *et al*., 2020; Lippke *et al*., 2011). The long design service life of buildings (50-100 years) enables these carbon stocks to be kept for many years, and the cascading use of wood can extend the products' life significantly until the end-of-life process converts them into biofuels, to be used as substitutes for fossil fuels.

Engineered wood products are wood derived composites that can perform a wide variety of functions in buildings construction, from formwork, cladding, roofing, and structural sheathing to load-bearing elements. The products can be divided into load-bearing, including glued laminated timber (glulam), cross-laminated timber (CLT), laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL); and non-load-bearing, comprising plywood, fibreboard, particle board, and oriented strand board (OSB). In what regards timber multistorey structures, this large palette of options can be reduced to three main products:

- **CLT:** Composed of dimensional lumber layered transversely and glued together under pressure with a structural adhesive, CLT can function as a two-way panel, i.e., distribute the load between two opposite directions, in walls, floors and roofs. Typically, the panels are formed with 3, 5, 7, or 9 layers that range between 20 and 40 mm in thickness and can add up to a 60 to 320 mm-thick panel. The elements can vary from 2.40 to 3.00 m in width and have a maximum length of 15 m. CLT may also be used to produce composite modules with concrete that aim to improve sound insulation, fire resistance, and bending-stiffness (Quang Mai *et al*., 2018).

- **Glulam:** Produced by bonding together, with a structural adhesive, several layers of timber laminations that run parallel with the element's length. Glulam's most important characteristic is its ability to take almost any shape and length without needing large solid timber pieces. This can be achieved by shaping each lamination individually and lengthening them with finger joints. Glulam's design flexibility enables it to be present in the form of load-bearing columns or beams in both concert halls and common dwellings.

- **LVL:** Fabricated with wood veneers of approximately 3 mm in thickness that are cut from rotating softwood logs and are then laminated together with structural adhesives, LVL is typically used for horizontal elements such as beams, I-joists and panels in floors or roofs.

2.1.4 **Mid- and high-rise buildings**

The use of EWP, especially CLT and Glulam, in mid- and high-rise buildings is becoming more and more common. Listed below are some examples of already existing buildings designed with timber structures. Note that some of these buildings have concrete elements (e.g., the building core) to provide additional stability.

Norway

- ZEB Laboratory, Trondheim — 4 storeys (CLT and Glulam)
- Svartlamoen housing, Trondheim — 5 storeys (CLT)
- Moholt 50|50, Trondheim — 9 storeys (CLT, Glulam and LVL)
- Treet, Bergen — 14 storeys (CLT and Glulam)
- Mjøstårnet, Brumunddal — 18 storeys (CLT and Glulam)

Sweden

- Nodi, Gothenburg — 5 storeys (CLT and Glulam)
- Strandparken, Sundbyberg — 8 storeys (CLT)
- Trummens Strand — 8 storeys (CLT)
- Sara Cultural Centre, Skellefteå — 20 storeys (CLT and Glulam)

Finland

- Wood City Supercell, Helsinki — 8 storeys (CLT and LVL)
- HOAS Tuuliniitty, Espoo — 13 storeys (CLT)

United Kingdom

- Whitmore Road, London — 5 storeys (CLT)
- Bridport House, London — 8 storeys (CLT)
- Stadthaus, London — 9 storeys (CLT)
- The Cube, London — 10 storeys (CLT)

Netherlands

- HAUT, Amsterdam — 21 storeys (CLT and Glulam)

Germany

- e3, Berlin — 7 storeys (CLT and Glulam)

Austria

- Mühlweg, Vienna — 4 storeys (CLT)
- LifeCycle Tower ONE, Dornbirn — 8 storeys (Glulam)

Switzerland

- MFH Holzhausen, Steinhausen — 6 storeys (CLT)

France

- Hyperion, Bordeaux — 16 storeys (CLT and Glulam)

Portugal

- Redbridge School, Lisbon — 4 storeys (CLT and Glulam)

Australia

- Monash University Gillies Hall, Frankston — 7 storeys (CLT and Glulam)
- International House, Sidney — 7 storeys (CLT and Glulam)
- Forté, Melbourne — 10 storeys (CLT and Glulam)
- 25 King, Brisbane — 10 storeys (CLT and Glulam)

Canada

- Origine, Quebec City — 13 storeys (CLT and Glulam)
- Brock Commons, Vancouver — 18 storeys (CLT and Glulam)

2.2 Life cycle assessment

The Life Cycle Assessment (LCA) aims to quantify product related environmental impacts; it can serve as a tool for manufacturers to identify hotspots in the production chain, help consumers make a conscious choice between products or even provide support for policy makers' decision-making process. First defined by the Society for Environmental Toxicology and Chemistry (SETAC) at the end of the 20th century, LCA is a method of evaluating the environmental burdens associated with a product or service (hereafter referred as product) by identifying its potential impacts on the environment throughout its life cycle, from raw material extraction and processing over manufacturing, distribution, use, recycling, and final disposal. These environmental burdens can be in the form of emissions to the atmosphere, water effluents, solid waste, or resource consumption.

2.2.1 **Normative references and guidelines**

To guarantee LCA quality and consistency, the International Standardization Organization (ISO) has developed ISO 14040 and ISO 14044, describing general principles, structure, and requirements to properly conduct an LCA; and ISO 21931-1, which focus on building environmental performance assessment:

- ISO 14040:2006, *Environmental management – Life cycle assessment – Principles and framework* (ISO, 2006a);
- ISO 14044:2006, *Environmental management – Life cycle assessment – Requirements and guidelines* (ISO, 2006b);

- ISO 21931-1:2010, *Sustainability in building construction — Framework for methods of assessment of the environmental performance of construction works — Part 1: Buildings* (ISO, 2010).

At European level, CEN/TC 350[1] provides a general framework for sustainability assessment of buildings in the European standard (EN) EN 15643, regarding environmental, social, and economic performance:

- EN 15643:2021, *Sustainability of construction works - Framework for assessment of buildings and civil engineering works* (European Committee for Standardization, 2021);

Building on the previous ISO guidelines CEN/TC 350 elaborated two more standards, providing general calculation rules for an analysis at building level (EN 15978) and at product level (EN 15804):

- EN 15978:2011, *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* (European Committee for Standardization, 2011a);
- EN 15804:2012+A2:2019, *Sustainability of construction works – Environmental product declarations - Core rules for the product category of construction products* (European Committee for Standardization, 2011b).

Additionally, European Commission's Joint Research Centre (JRC) published a set of documents in line with the ISO 14040 and ISO 14044, constituting the International Reference Life Cycle Data System (ILCD) Handbook, which seeks to provide "*governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments*" (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Drawing on the ILCD Handbook, EN 15978 and EN 15804, EU's EeBGuide project organized an LCA guidance document directed towards the buildings industry (EeBGuide Project, 2012). IEA EBC[2] Annex 57 also delivered a set of LCA guidelines (IEA EBC, 2016) focusing on evaluating embodied energy and GHG emissions belonging to building construction. These guidelines are currently being broaden by the ongoing Annex 72, which is furthering the research conducted in Annex 57 by including operational impacts.

2.2.2 **Methodology**

The LCA methodology, according to ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b), should encompass four phases, independently of the type of product and scope of the assessment:

− **Goal and scope definition:** Describes the application, purpose and targeted audience of the study and specify the function; functional unit, or functional equivalent for the building sector; and system boundary of the product system along with all the assumptions made. The specification of the functional unit is especially important in studies that aim at comparing different systems;

[1] European Committee for Standardization, Technical Committee 350 – Sustainability of construction works.
[2] International Energy Agency's Energy in Buildings and Communities Programme.

– **Life cycle inventory analysis (LCI):** Includes the process of data collection and quantification of input (e.g., raw materials or energy) and output flows (e.g., air emissions or solid waste), acquired from LCA databases or environmental product declarations (EPDs), for the product system's assessed life stages;

– **Life cycle impact assessment (LCIA):** Aims to evaluate the significance of potential environmental impacts through the classification and characterization of the inputs and outputs collected in the LCI. Each of these inputs and outputs is assigned to an environmental impact category (e.g., global warming or acidification) and subsequently converted into an environmental impact using a characterization model (e.g., CML or ReCiPe);

– **Life cycle interpretation:** Critically reviews the findings according to the established goal and scope, formulates conclusions and improvement measures to reduce the environmental impacts associated with the product system, and assesses the sensitivity and uncertainty of the results. The interpretation of the results can also be carried out at the end of each phase, for instance, to perform a review of the scope definition or data quality.

2.2.2.1 **Type of LCA approach**

Despite the various ISO standards regarding the LCA methodology (ISO, 2006a; ISO, 2006b), the approach for quantifying the direct and indirect impacts in the LCI phase is not standardized. As a result, when looking at several studies, a reader often comes across results from similar products (e.g., a building's structural frame) but where the environmental burdens have been quantified in different ways, leading sometimes to very different estimates (Säynäjoki *et al.*, 2017b).

To quantify the environmental impacts of products, LCA practitioners often adopt one of three approaches, a bottom-up approach in which the impacts are estimated based on a model of the physical flows in the product's process chain (Process-based), a top-down approach that uses environmentally extended input-output tables to relate the production of a particular quantity of a product in monetary units to a specific quantity of, e.g., emissions (Input-output), or finally, a hybrid approach that combines process-based data with input-output data.

According to ISO 14040:2006 (ISO, 2006a), a system boundary should be defined in a way that all its flows are elementary flows (i.e., flows from or to the environment, such as raw materials and primary energy consumption, solid waste production and emissions to air and water). But unless the product system is an isolated system (i.e., all inputs feeding the process-chain come directly from its processes), its boundary must be expanded to include the whole supply chain (stretching, in some cases, over the entire economy). Due to the difficulty in gathering process-specific data for all processes and the complexity of managing such comprehensive systems — that would radically increase the duration and cost of the LCI phase —, cut-off criteria are often applied in LCA practice to omit non-relevant processes from the system. Yet, this simplification causes truncation errors that can result in an underestimation of the environmental impacts of products, because while the processes might not be relevant, their overall impact can be non-negligible. Process-based LCAs are therefore often known to produce underestimations of the environmental impacts of products (Suh *et al.*, 2004).

Input-output LCAs, on the other hand, can cover more comprehensive systems by using inter-industry matrices, that consider the interdependencies between production activities (sectors) — i.e., the amount required from one industry in order to produce one monetary unit in another industry — , and that are integrated with sectorial environmental data (e.g., matrices containing emission coefficients per monetary output for each of the sectors) to estimate the environmental externalities of the systems (European Commission - Joint Research Centre - Institute for Prospective Technological Studies, 2006).

But there are also limitations in input-output LCAs, namely the low level of data granularity resulting from the aggregation of industries into sectors. In input-output tables, industries are grouped into sectors, and it is possible that different industries with considerably different carbon footprints are aggregated in the same sector and consequently represented by the same weighted average emission coefficient, which can lead to impacts being underestimated or overestimated — this problem is especially relevant in product-specific assessments. Moreover, originally, an input-output LCA can only address the production phase of a product, leaving the use and end-of-life phases to be assessed by other methods. Other specific problems associated with this approach, that bring uncertainty to its results, include the use of economic data and of environmental data with temporal differences (that can lead to errors due to changes in prices or in technology) and the use of domestic data (i.e., national IO tables) on product systems with imports from foreign industries (Suh and Nakamura, 2007; Carnegie Mellon University Green Design Institute, 2008).

Despite both methods having inherent limitations, input-output LCAs are usually found to estimate higher environmental impacts than process-based ones, due to having broader system boundaries (Säynäjoki *et al.*, 2017b). In order to overcome these limitations, researchers have developed an alternative approach known as '*hybrid*'. Though there are several methods that are regarded as hybrid, they all share a common principle: improve the comprehensiveness and accuracy of LCI, by combining process-specific data with input-output data, to produce more accurate and reliable assessments (Crawford *et al.*, 2018).

2.2.2.2 **Building assessment specific concepts**

The redefinition of previously existing concepts or the creation of new ones in the European Standards brough some methodological differences to the environmental assessment of buildings; this section aims at providing insight into the most relevant variances.

- **Functional unit / functional equivalent**

The term functional unit is identified in ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) as the quantification of a product system's performance, and according to EN 15804 (European Committee for Standardization, 2011b) it must comprise the function (e.g., reduce heat transfer), quantity (e.g., 1 m^2), duration (e.g., design life span of 50 years), and quality (e.g., minimum U-value of 0.5 $W/m^2 \cdot K$) of the product. While the functional equivalent, defined in EN 15978 (European Committee for Standardization, 2011a), is specific to building assessment and should include the building type (e.g., office or dwelling), relevant technical and functional requirements (e.g., national and client's specific requirements), the pattern of use (e.g., occupancy), and the required service life.

- **System boundary**

Setting a system boundary in the LCA methodology involves the process of defining the product life stages considered in the assessment. For building assessment, EN 15978 (European Committee for Standardization, 2011a) specifies that each life stage is subdivided into modules linked to specific processes or operations, as displayed in Figure 2.

While all modules from A1-C4 relate to actual building life stages and therefore cover the associated environmental impacts, module D only incorporates the net benefits from reuse, energy recovery and recycling beyond the system boundary.

The various product life cycle concepts generally utilized in building assessment (cradle-to-gate and cradle-to-grave) are associated in EN 15978 (European Committee for Standardization, 2011a) with the following life stages modules:

- Cradle-to-gate – A1 to A3;
- Cradle-to-site – A1 to A5;
- Cradle-to-grave – A1 to C4.

An additional concept (cradle-to-cradle), usually linked with the circular economy concept, is applied when the end-of-life disposal corresponds to a recycling process:

- Cradle-to-cradle – A1 to A1.

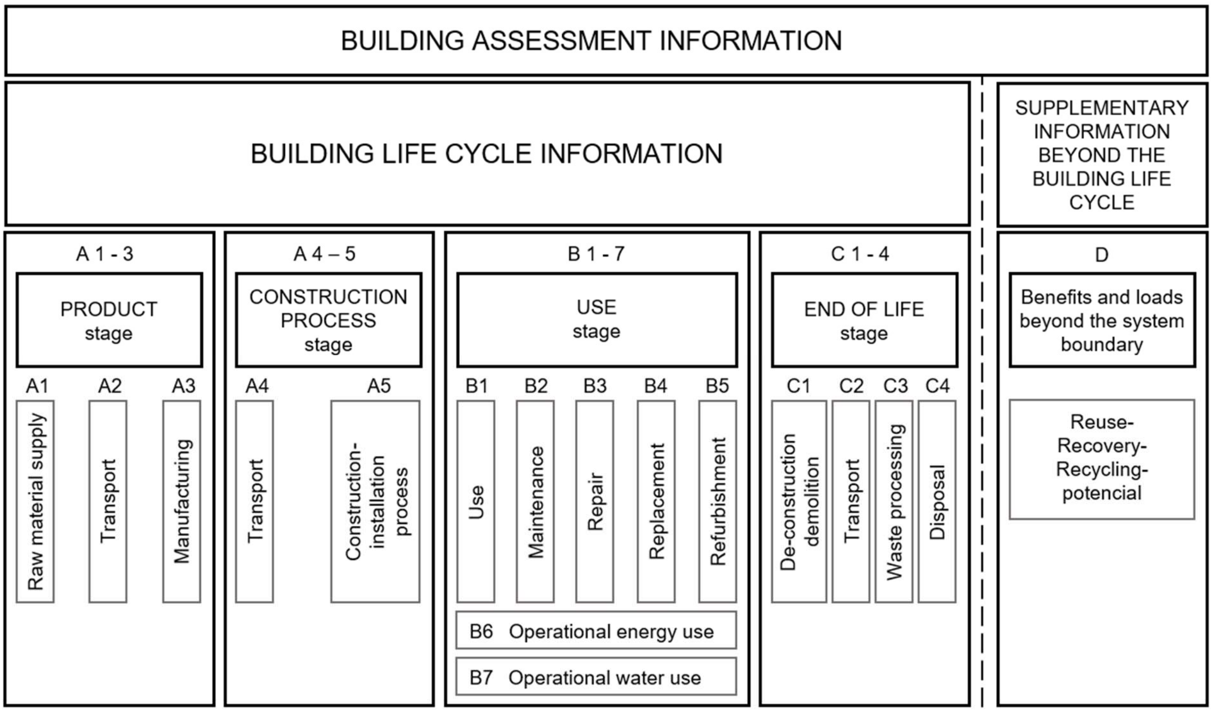

Figure 2. Different stages of the building assessment displayed in modules (adapted from EN 15978:2011 [European Committee for Standardization, 2011b]).

Chapter 3

Meta-analysis: Assessing the influence of different factors on embodied GHG emissions

In 1976, Gene V. Glass, an American statistician, applied the term "*meta-analysis*" to define "*the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating findings*" (Glass, 1976). Although first proposed in social science literature, today this method is widely used in the biomedical sciences and is becoming an emerging trend in other scientific areas of research, namely in LCA studies. By being beneficial for the comprehension of the magnitude and variability of the impacts and of the parameters driving the results, the meta-analysis can serve as a valuable tool for strengthening LCA's relevance in supporting decisions (Brandão *et al.*, 2012).

3.1 Scope

Buildings' environmental impacts can be broken into two categories based on their origin: operational impacts and embodied impacts. Operational impacts arise during the occupancy stage of a building's life cycle from, as suggested by the name, the processes related to its operation (e.g., lighting, heating, cooling and ventilating spaces, heating water, and powering appliances). Embodied impacts, on the other hand, stem from the manufacturing and transportation of building materials and operation of construction machinery required for the erection, retrofit and dismantling of the building.

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, though it could be argued that, from a designing standpoint, the latter could be necessary to comply with fire resistance requirements of some timber structures and therefore should be considered structural. Nevertheless, its inclusion would have caused inconsistencies between the cases' material boundaries, due to the heterogeneity of studies in reporting specific data about the fire-rated gypsum-based products, and so were left out.

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), since the impacts originated during those stages are, to some extent, independent of the building site and its constraints. The construction process modules (i.e., A4 to A5) are determined by, among other factors, the distance between the building materials' factories and the building site, the available methods of transportation, and the constraints of the buildings site. For comparison purposes these stages, A4 to A5, were left out from the analysis. The end-of-life stages and the net benefits from reuse, energy recovery and recycling beyond the system boundary were also excluded due to the lack of studies providing that information. The terms "embodied", therefore, will be used hereafter to refer to the environmental impacts stemming only from stages A1 to A3.

Buildings' environmental impact on the climate is commonly expressed by their carbon footprint or GWP, measured in $kgCO_2$-eq (kilograms of CO_2 equivalent). During the production of building materials several greenhouse gases (GHGs) are released to the atmosphere, namely carbon dioxide, methane and nitrous oxide. This unit, $kgCO_2$-eq, was adopted worldwide to allow the comparison of the effect of different GHG (that absorb different amounts of energy and have different lifespans) and it measures the amount of energy that one gas will absorb over a certain time frame relative to the amount of energy that CO_2 will absorb over that same time frame. However, recently, studies have been using a variation of 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.*, 2020b). This unit, $kgCO_2$-$eq/m^2.y.$, normalizes 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, which is based on the traditional design life chosen for buildings by structural engineers. In order to stay in line with the results of these recent studies, and to allow for comparison with their figures, this unit was chosen as the reference unit for this study.

3.2 Literature review

Compiling a database of studies based on a systematic literature review (SLR) can be a very time-consuming process, depending on the subject and volume of research available around it. A SLR, as suggested by the name, systematically (i.e., following a well-defined methodology that ensures the replicability of the search) gathers, filters, and combines literature to answer one or more research question that were formulated beforehand. During this process, a number of sources, that can range from bibliographic databases, such as academic publishers, to available sources of grey literature (e.g., technical reports and theses), are selected to locate studies related to the topic of interest; the search for these studies is achieved by using predetermined keywords that are inherently linked to the research question(s). Once the sources and respective keywords have been selected, search results can start being filtered by their title and listed into the initial sample. Later, when the full listing is completed, the sample should be refined by undergoing a screening process, in which a set of inclusion and exclusion criteria filter the studies that will make part of the final sample (Littel *et al.*, 2008; Pati and Lorusso, 2018). This process comprises two phases, abstract review and full article review, with the latter being commonly executed simultaneously with the data extraction.

Systematic literature searches can be complemented with a procedure known as the snowball approach. Snowballing is an iterative process that uses the reference list and, if available, the citing articles of an initial set of literature as a source for gathering more literature. In each iteration. the articles are first selected by looking at their titles in the reference list and then by checking their place of reference. As the articles are added to the sample after being fully reviewed (abstract and full article), they can also be included in a new set for snowballing (Wohlin, 2014). By using the final sample of the systematic search as an initial set for this procedure, the breadth of the sample can be, in some cases, substantially broaden due to the inclusion of studies that did not show up during the database search.

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, detailed in Table 1, 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. The snowballing phase was concluded in March 2019 and added 43 scientific papers, 9 reports, 2 master theses and 1 book. In total, the research compiled 325 case studies from the systematic research and 331 case studies from the snowball approach, resulting in a final sample of 656 case studies (Röck *et al.*, 2020b).

Table 1
Overview of Annex 72 systematic literature search.

Database	Scopus
Keyword String	[(LCA OR life cycle assessment) AND buil* AND embodied]
Keyword Location	Article title, Abstract, Keywords
Criteria	English only
	Excluding grey literature
	Without time boundaries
Date of conclusion	July 2018
Initial search	369 papers
Filtering	
Title review	349 papers (-20)
Abstract review	181 papers (-168)
Full article review	94 papers (-87)

After questioning the corresponding author of the research team that developed the systematic search about the possibility of having the literature database made available for this study, the author kindly provided a Microsoft Excel file containing the reference list. This list, however, compiling 313 cases, was shorter than the aforementioned final sample because it was limited to reinforced concrete and timber structures. This reduction became even more significant when the full articles were reviewed within the scope of this study. That is to say, studies that did not provide enough information to calculate the structural frame embodied GHG emissions or analysed buildings lower than 4 storeys above ground were excluded. Furthermore, papers that, e.g., analysed different refurbishment or retrofit scenarios and provided several case studies of the same building, were reduced to one case if the structural system was common between all scenarios. In addition to this, studies that were not available for access were also removed. With these additional criteria, the sample saw a reduction to only 10 cases.

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 to exclude studies that did not specify the structural frame embodied GHG emissions or provide enough information to enable its calculation, e.g., total embodied GHG emissions and percentage contribution of the structural frame or structural materials quantities and respective emission factors. As in the first snowball procedure, this second one also integrated the input from experts in the field for additional relevant LCA studies, namely studies comparing timber with reinforced concrete.

Following the same methodology as Röck *et al.* (2020b), 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, were too labelled as not providing enough information. However, if this information could be found in another publication, e.g., an architecture book or a different scientific paper, the study would be kept in the sample. The definitions of gross floor area and net floor area here applied are consistent with ISO 6707-1:2020 (ISO, 2020) and indicates, respectively, the area enclosed by the outer surface of the external walls and the area measured from the inner face of the external walls; terms such as 'total floor area', 'construction floor area' and 'building area' were assumed to share the same definition with GFA., and, similarly, 'gross internal floor area' and 'total usable area' were adopted as being equivalents to NFA.

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 52 cases. The final database, organized in a Microsoft Excel file, followed the same structure as the original list provided by Röck *et al*. (2020b), detailing the studies' source (i.e., if the studies were collected in the original search through the systematic search or the snowball approach, or if they were added by this study in the second snowball procedure), author(s), year of publication, title, journal title and DOI/reference. With the studies fully referenced, the next step in the research process was to extract the key information that would be relevant for the analysis.

3.3 Data extraction

In order to optimize the research time, this stage was conducted simultaneously with the full article reviewing process. Yet, before the information could start being extracted and introduced in the Microsoft Excel file, it was necessary to decide what data would be relevant for the upcoming analysis. To that end, 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, 5 detailing the assessed building characteristics and 1, comprising 17 subfields, one for each life cycle module, reporting the GHG emissions throughout the building life stages. The 7 fields addressing the methodology of the assessment had the purpose of providing information that would enable to comprehend how comparable the cases were and, additionally, serve as a mean to assess the current state of LCA reporting practice in literature. As for the field reporting the GHG emissions, it was divided in subfields to provide a more flexible structure that could be adapted for each case. This would allow stages to be easily arrayed in Microsoft Excel by merging the respective columns together when studies clustered LCA stages together (e.g., A1-A5) instead of reporting them separately. Table 2 presents the different fields that characterize the LCA methodology and the building along with the different input options and data examples. If there was any additional information that was relevant about some specific cases, such as the type of timber system used in timber buildings, it would be added as a comment.

Table 2
LCA methodology information retrieved from the studies in the data extraction stage.

Methodological aspects	
Methodology	Process-based (PB), input-output (I-O) or hybrid (HYB)
Impact Assessment Method	e.g., GWP 100 IPCC 2013 or CC 100 ReCiPe Midpoint (H)
Database	e.g., ecoinvent v3.6 or EPDs
Software	e.g., SimaPro v9.1 or Microsoft Excel
Floor unit	GFA, NFA or equivalent terms
RSP (Reference Study Period)	<no. of years>
Assessed Structure	S (superstructure) or W (substructure and superstructure)
Building characteristics	
Main material of structural system	RC (reinforced concrete) or T (timber)
Number of floors	F<floors above grade> + B<basements> (e.g., F5+B2)
Location	<city>, <country> OR <city>, <state>, <country>
Type of use	Residential, Office, Retail, Hotel, Educational or Mixed-use
Structural weight (kg/m^2)	<weight of structural materials per GFA>

As already stated in section 3.2, the scope of this study was limited to the embodied GHG emissions of the structural frame and, therefore, only the studies that reported it directly or provided enough information to calculate it were kept in the database. 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 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 (e.g., structural frame, envelope and partition walls) but instead by building materials (e.g., concrete, reinforcing steel, CLT, glulam, LVL, glass, brick, gypsum, etc.), 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. Due to the unavailability of data in numerical form, some of the figures considered throughout this process had to be extracted from bar charts. This made necessary to resort to a software tool that enabled to reverse engineer the bar charts and extract their numerical data: the WebPlotDigitizer (Rohatgi, 2020), a free, user-friendly software, both available as a web and desktop application, that allows users to upload an image file, calibrate the chart axes and manually or semi-automatically extract data points from several chart types. Drevon *et al*. (2017) investigated the replicability of the data extracted with this software and the results showed a high level of intercoder reliability (the extent to which two, or more, different researchers extracting the same data points agree on their values) and validity. Nonetheless, all the data points were reviewed at least once to ensure the consistency of the data.

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 $kgCO_2\text{-}eq/kg$). Table 3 summarizes the data extraction approaches by describing the type of data necessary for each and quantifying the number of cases included in the final meta-analysis sample.

Table 3
Overview of the data extraction approaches and respective number of cases in the final sample.

Data Extraction	Type of data necessary	Number of cases
Direct	Structural frame embodied GHG emissions	12
Approach 1	Total embodied GHG emissions × [Percentage contribution of the structural frame OR Sum of the percentage contribution of the structural materials]; Sum of the absolute contribution of the structural materials.	39
Approach 2	Structural materials quantities × Structural materials emissions factors.	11

3.4 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 *$kgCO_2$-eq/m^2·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.

$$GHG_{RSP50} = GHG_0 \times \frac{RSP_0}{50} \tag{1}$$

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. When the information needed for the calculation of a specific conversion factor, namely the NFA and the GFA, was not available, a constant value of 0.8 was assumed. This value is consonant with the net-to-gross factor chosen by Röck *et al.* (2020b), which is based on a European Commission Directive (European Commission, 2015). Net-to-gross conversion factors usually range from 0.70 to 0.85 (Huang *et al.*, 2018; Passer *et al.*, 2012), however, specific values may vary between different building types and world regions due to differences in architectural practices, traditions or building codes (Säynäjoki *et al.*, 2017a). To assess the adequacy of the value chosen for the sample, a selection of the studies that provided the NFA and the GFA, or the specific conversion factor, was carried out. This selection resulted in a set of 19 buildings (2 in Asia, 1 in Oceania and the remaining in Europe) with an average conversion factor of 0.79 and a first and third quartile of 0.75 and 0.84, respectively. This seemed to suggest that the constant of 0.8 would be appropriate for the analysis. 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.

$$GHG_{GFA} = GHG_0 \times f_{net-to-gross} \tag{2}$$

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}.

3.5 Statistical analysis

The final sample comprised a total of 62 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. The data of these cases can be found in Appendix B (Table A-3). The cases were spread across 17 countries covering four geographic regions: North America, Europe, Asia and Oceania. Yet, as can be seen in Table 4, their distribution across these regions was not even. In fact, 54% of the cases were located in Europe, and the remaining 25%, 14% and 8% were located in North America, Asia and Oceania, respectively. The complete list of the geographic distribution of the sample, detailing the number of cases by country, can be found in Appendix A.1 (Table A-1).

Table 4
Geographic distribution of the final sample, detailing the number of cases by region.

Structural material	Geographic location	Number of cases
Reinforced Concrete	North America	11
	Europe	21
	Asia	9
	Oceania	3
Timber	North America	2
	Europe	10
	Oceania	1
Timber (w/ CO_2 sequestration)	North America	1
	Europe	3
	Oceania	1

The statistical analysis followed an approach known as exploratory data analysis (EDA). First introduced in 1977 by the America mathematician John Wilder Tukey, EDA is used to analyse data sets and summarize their main characteristics, before making any assumptions, in order to identify patterns and relationships between the variables. In this approach, the data set is examined from several distinct perspectives by combining different sets of variables with different data visualization methods (IBM Cloud Education, 2020; Tukey, 1977).

The different data visualization methods that were used in the analysis included the scatter plot, the map chart, and the box plot. The box plot is a data visualization method that succinctly describes the main aspects of a data set through a rectangle (box) plotted in a single axis chart. It can graphically depict the main features of a distribution (central tendency, variability, skewness and existence of outliers) and allows several distributions to be plotted together, enabling their comparison. The box is vertically delimited by the first and third quartile, that correspond, respectively, to the lower and upper end of the box, and is extended by two exterior lines, known as whiskers, that stretch vertically from the limits of the box and end, for the lower whisker, on the lower adjacent value and, for the upper whisker, on the upper adjacent value. The whiskers represent the observations that are outside the range of the first and third quartile but that are within the extremes of the data set, i.e., the lower and upper adjacent value. Additionally, the whiskers can be complemented by the individual plot of outlier points, i.e., data points that have such a considerable difference from the other observations that exceed the extremes of the data set and hence need to be individually displayed.

In statistics, the first and third quartile of a distribution correspond to the points that are exceeded, respectively, by 75% and 25% of the data. The difference between these points, i.e., the third and the first quartile, is used as a measure of variability, known as the interquartile range (IQR). In addition to providing information about the variability of the data set, the first and third quartile are also used to calculate the lower and upper adjacent value, which, as explained before, define the extremes of the data set, and correspond, respectively, to the furthest point that is within one and a half times the interquartile range from the lower end of the box and from the upper end of the box.

In what regards the main features of the data set, the central tendency of the distribution is given by the median, marked by a horizontal line inside the box, and the variability is measured by the height of the box, which represents the interquartile range. The skewness of a distribution can be assessed, based on Bowley skewness measure (Bowley, 1907), by observing and comparing the distance from the median to the first and third quartile, i.e., the distance from the median line to the lower and upper end of the box. If the median line is closer to the lower end of the box, the distribution is positively skewed, if the opposite happens (i.e., the median line is closer to the upper end of the box), than the distribution is negatively skewed. When the median line is equidistant from both ends of the box the distribution is said to be symmetric.

3.5.1 **Type of structural material: Reinforced concrete and timber**

The first aspect that was examined was the type of structural material. In the sample that was compiled for the meta-analysis, based on literature, — and that is displayed chronologically by type of structural material in Figure 3 — it appears that reinforced concrete buildings' LCAs started being more regularly published before timber buildings' LCAs. Based on the year of publication of the studies, it seems that in 2008 reinforced concrete buildings' LCAs were already being published on a regular basis. Timber buildings' LCAs, on the other hand, only appear to have become more consistently published almost half a decade later, in 2012; yet the publication of studies that accounted for the effect of CO_2 sequestration appeared to be still only sporadic in 2020. In 2013, the annual number of published LCAs on reinforced concrete buildings and on timber buildings saw an increase that continued throughout the following years, reaching its peak in 2016 — a year after the Paris Agreement had been adopted.

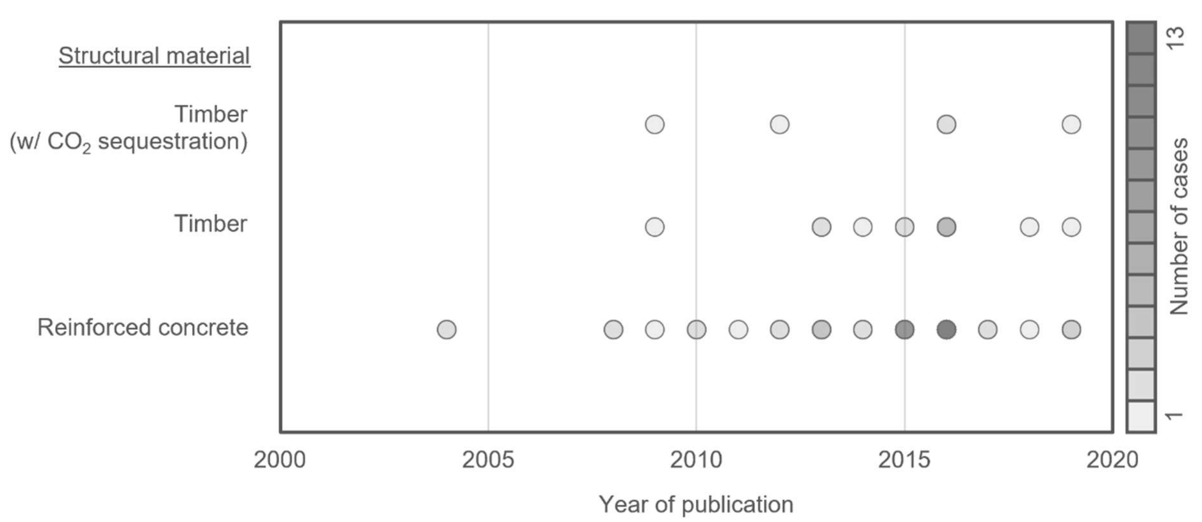

Figure 3. Distribution of the cases through time by year of publication and by structural material.

Figure 4 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 due to the overall reduction of the embodied GHG emissions. This second timber interval ranged between -0.9 and 1.4 kgCO_2-eq/m^2.y and measured 2.4 kgCO_2-eq/m^2.y in length.

In terms of skewness, the reinforced concrete distribution was positively skewed — which meant that the cases that had values of embodied GHG emission below the median differed less than the cases that were above it; the timber distribution that did not consider CO_2 sequestration was symmetrical and the one that did was negatively skewed — i.e., the values below the median differed more than the ones above it.

On average, based on the arithmetic mean and excluding the outliers, 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.

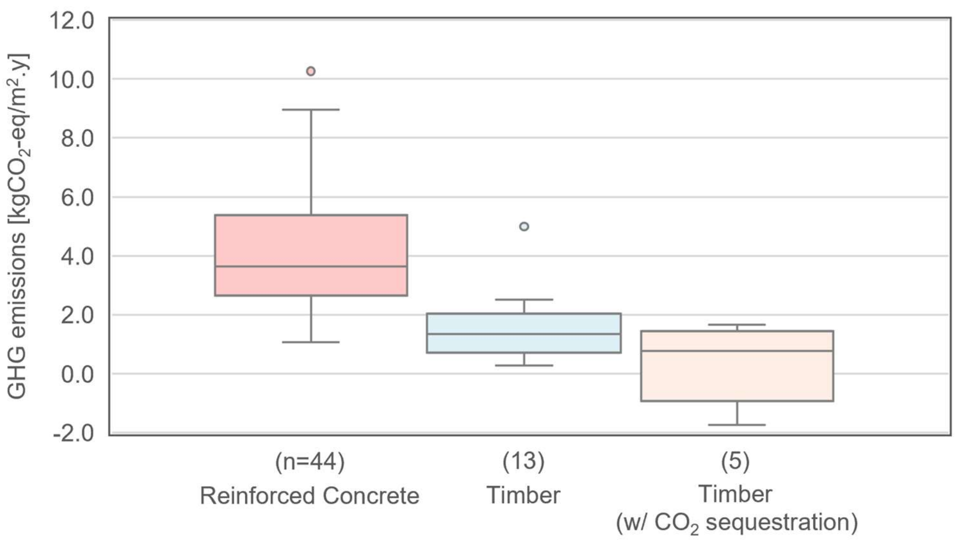

Figure 4. Box plot of the distribution of the embodied GHG emissions in reinforced concrete and timber buildings.

If we plot the embodied GHG emissions with the total height of buildings (measured by the total number of storeys above foundations), as displayed in Figure 5, it is possible to see that, overall, for the same number of storeys, timber buildings had lower embodied GHG emissions than reinforced concrete buildings. In comparison to reinforced concrete buildings, timber buildings' values varied very little, in spite of the height of the buildings. The vast majority of the timber cases (19 of the 21 cases) clustered together between 0.1 and 2.5 kgCO2-eq/m^2.y, regardless of the total number of floors and the inclusion of the effect of CO_2 sequestration, whereas reinforced concrete cases fanned out and reached substantially higher values.

In timber buildings, the predominance of cases constructed with glulam or CLT displays what has already been shown in Chapter 2 (section 2.1.4), until today, mid- and high-rise timber construction relied mostly on these two EWPs. In terms of the environmental performance of the different systems (carbon footprint), the sample was too small and diverse to allow for a sound comparison between them, nonetheless, they seemed to be fairly balanced between each other.

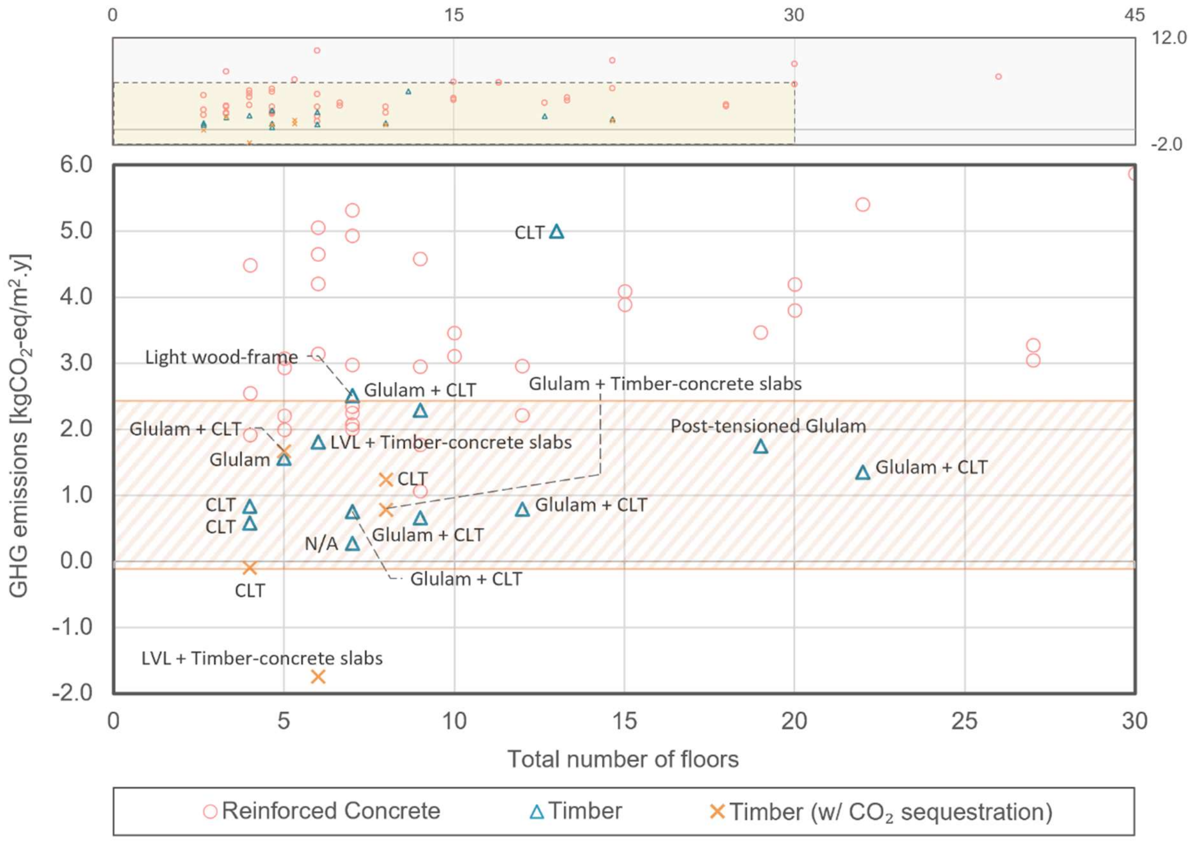

Figure 5. Scatter plot of the embodied GHG emissions as a function of the building height in reinforced concrete and timber buildings (with labels identifying the different timber systems).

Figure 6 displays the linear regression models between embodied GHG emissions and total number of floors for reinforced concrete buildings and for timber buildings. As can be seen, the models appear to suggest that as reinforced concrete and timber buildings become taller, their carbon footprint increases (not considering the effect of CO_2 sequestration). The rate at which this increase occurs, however, 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. The effect of considering CO_2 sequestration on the trend of timber buildings was not assessed due to the proximity of the observations. 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) — a slightly lower value than the one previously presented based on the difference between the means. It should be noted, however, that these trends must be taken with caution, as the total number of floors can only explain a small percentage of the variability of the carbon footprint around its mean (about 16% for the reinforced concrete subset and less than 10% for the timber subset), as displayed by the coefficient of determination, R^2.

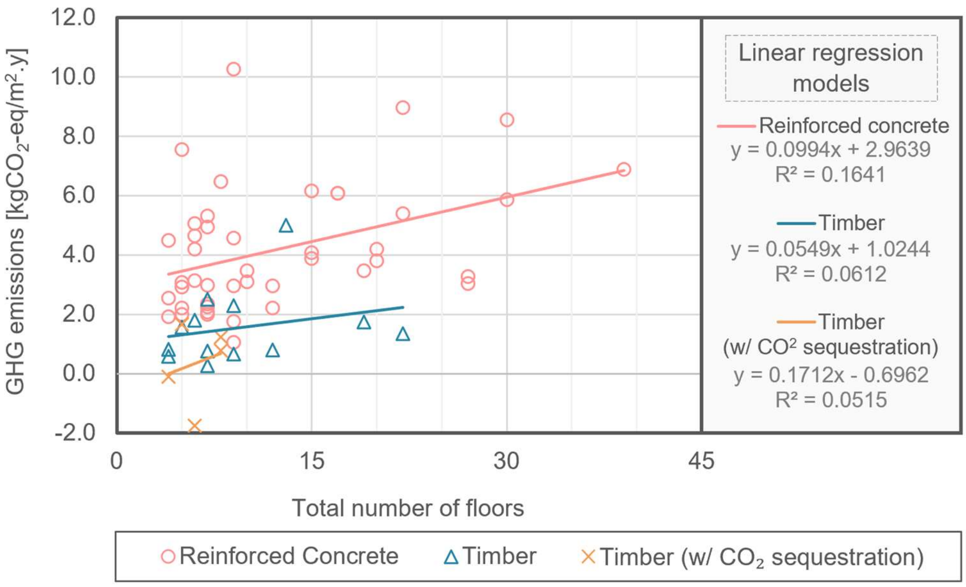

Figure 6. Scatter plot and linear regression models of the embodied GHG emissions as a function of the building height in reinforced concrete and timber buildings.

If we perform a similar analysis on the structural weight of buildings, i.e., on the mass of structural materials per unit floor area, reinforced concrete buildings appear, once again, to exceed most of the values of timber buildings, as can be observed in Figure 7. In absolute terms, reinforced concrete buildings ranged between 821 and 1,374 kg/m^2 (1st and 3rd quartile), and had an interval length of 553 kg/m^2 (IQR), while timber buildings ranged between 190 and 872 kg/m^2, and had an interval length of 682 kg/m^2. Since a building's structural weight is independent from the consideration of CO_2 sequestration in the LCA, for this part of the analysis the timber cases were grouped into just one subset.

In contrast to what was found in the analysis of the distribution of the embodied GHG emissions, where timber buildings varied substantially less than reinforced concrete buildings, here, it were the timber structures that showed a higher variability (in terms of IQR). In addition to this higher variability, timber buildings were also positively skewed — similar to reinforced concrete buildings —, indicating that the structural weight values that exceeded the median were more disperse than those that did not.

Based on the arithmetic mean (and discarding the outliers), reinforced concrete buildings used an average mass of structural materials per unit floor area of 1,092 kg/m^2, while timber buildings only used 541 kg/m^2. This resulted into a reduction of the structural weight from reinforced concrete to timber of 551 kg/m^2, which, in relative terms, translates into a 50% mass reduction per unit floor area.

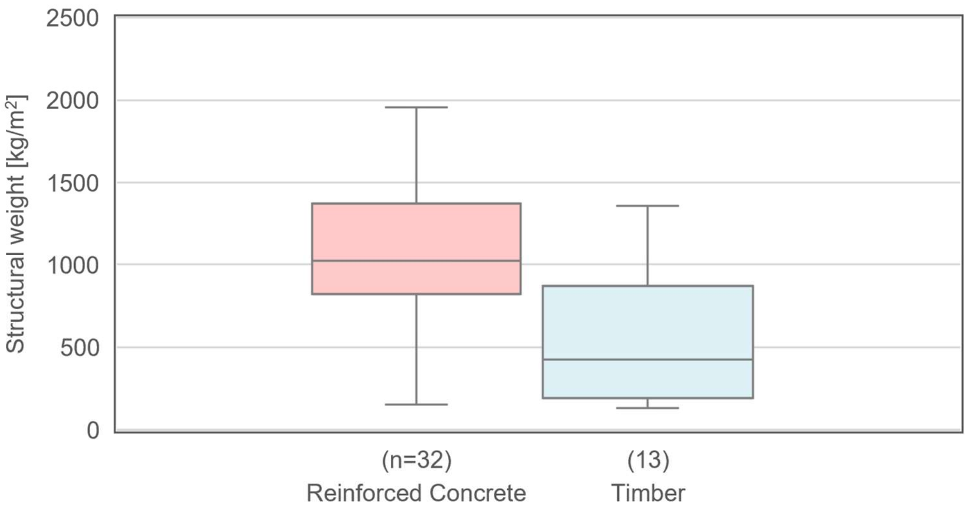

Figure 7. Box plot of the distribution of the structural weight in reinforced concrete and timber buildings.

By representing the structural weight with the total number of floors, as illustrated in Figure 8, a similar pattern to the one observed in Figure 6 arises, with the difference that there are fewer cases (due to the unavailability of data on the mass of the structural materials for some of the cases) and a single timber subset.

Once more, timber structures displayed, in general, lower values than their reinforced concrete counterparts. For the most part, buildings built with timber required less mass of structural materials to reach the same building height as those built with reinforced concrete. While timber cases concentrated mostly below 500 kg/m^2, and never reached 1,500 kg/m^2, reinforced concrete cases were virtually all (apart from one outlier) beyond 600 kg/m^2, reaching in some cases values close to 2,000 kg/m^2. The reinforced concrete case that had a structural weight under 600 kg/m^2, had a value almost six times lower than the next minimum value. When the study that provided this case and its calculations were reviewed, to find the reason behind this remarkably low structural weight, it was found that its mass of steel in proportion to its mass of concrete was substantially higher than in other cases. The origin behind this case's low structural weight will be more thoroughly investigated in section 3.5.5..

Looking at the linear regression models, as reinforced concrete buildings become taller, they appear to require more mass of structural materials per unit floor area. Timber buildings, on the other hand, display an opposite tendency; yet it should be noted that, in this model, the total number of storeys can only explain an exceedingly small fraction (0.5%) of the variability in the structural weight of timber structures. If instead of analysing all observations, we focus just on the low values, we can see that they appear to increase as the total number of storeys rises, both in reinforced concrete and timber buildings. For the same total number of storeys, the minimum structural weight of reinforce concrete buildings seemed to be about 500 kg/m^2 higher than the minimum value of timber buildings — which is in line with the difference of the means.

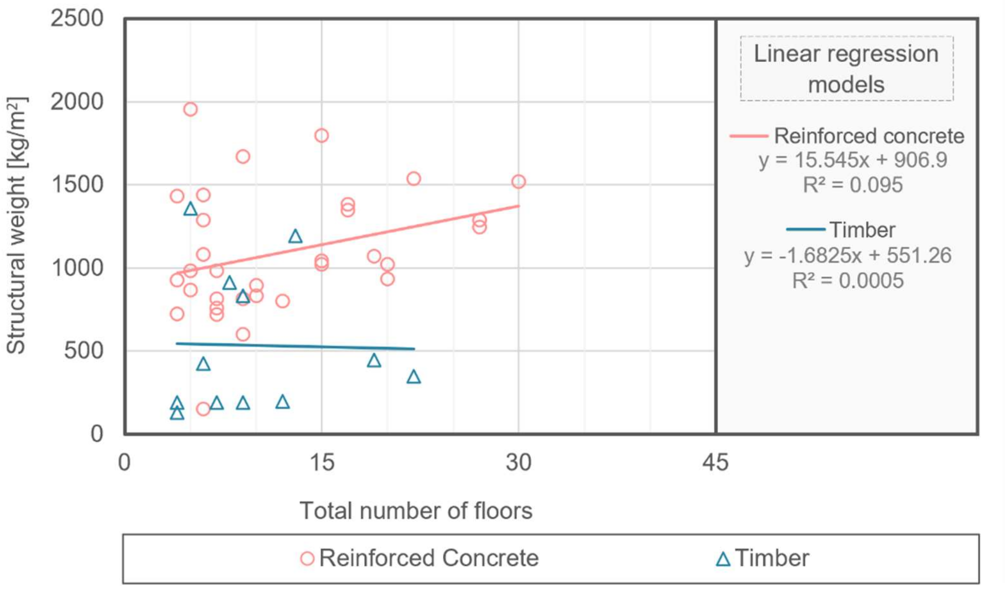

Figure 8. Scatter plot and linear regression models of the structural weight as a function of the building height in reinforced concrete and timber buildings.

Figure 9 shows the embodied GHG emissions in relation to the total number of floors of reinforced concrete and timber buildings. As can be observed, the carbon footprint of buildings tends to increase as the weight of the structural materials per unit floor area rises — which is understandable since the former is dependent on the latter. However, if we look more carefully and differentiate the different subsets, we can see that, while the timber cases that did not account for CO_2 sequestration followed a similar upward trend to reinforced concrete buildings, those that did, although also presenting an upward trend, had fairly lower embodied GHG emissions for the same structural weight. Additionally, it might also be noticed that the carbon footprint of the reinforced concrete case that had a remarkably low structural weight was not proportional to that value. Due to its extremely different structural weight, it was decided to omit this case from the reinforced concrete linear regression model.

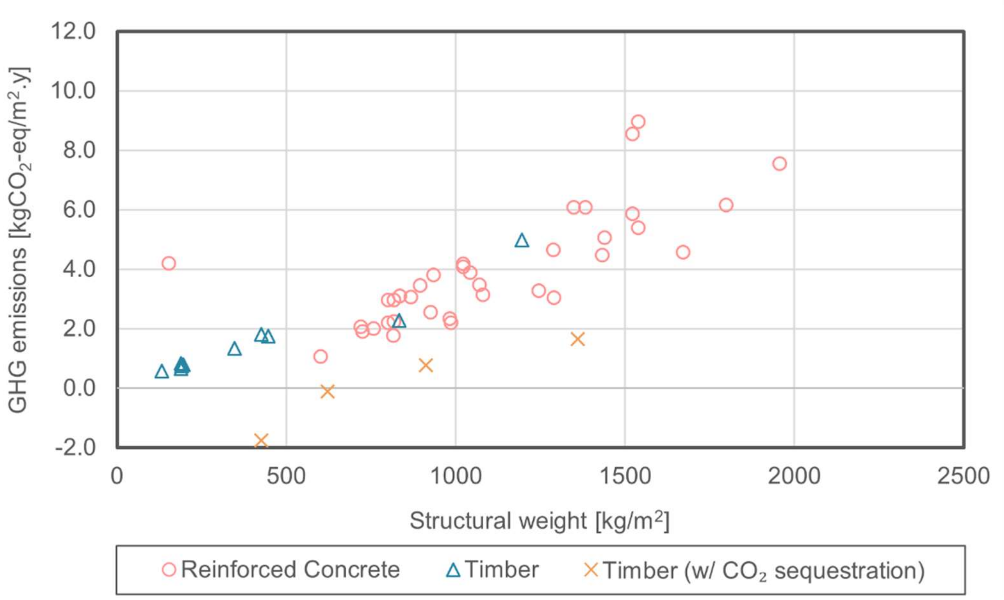

Figure 9. Scatter plot of the embodied GHG emissions as a function of the structural weight in reinforced concrete and timber buildings.

Based on the linear regression models represented in Figure 10, 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. In timber buildings, however, this increase appears to occur at a slightly slower rate — probably due to the presence of a point that was quite isolated and that deviated slightly from the general trend. When the effect of CO_2 sequestration was accounted for, the trend started at a much lower value (about 3 kgCO2-eq/m^2.y below) but the rate of the increase remained almost the same. Based on this trend, considering the effect of CO_2 sequestration appears to cause the embodied GHG emissions from material production of structures to be about 3 kgCO2-eq/m^2.y lower than what would be estimated if the effect was not considered and to be negative for structural weights below ~750 kg/m^2.

Finally, looking at the R^2, its high values seem to indicate that the relationship between the structural frame's carbon footprint and its weight per unit floor area was the strongest until here observed. Based on these values, 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).

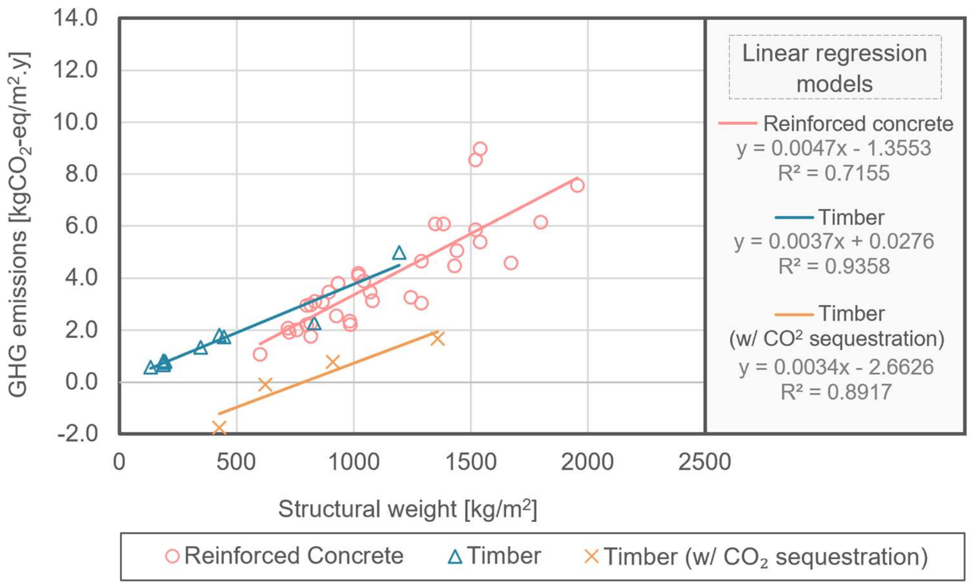

Figure 10. Linear regression models of the embodied GHG emissions as a function of the structural weight in reinforced concrete and timber buildings.

With the analyses of the type of structural system concluded, the next step in the analysis was to examine the influence of other factors on the embodied GHG emissions of buildings. However, due to the limited number of timber cases, only reinforced concrete buildings were addressed.

3.5.2 **Geographic location**

In order to understand how the values of reinforced concrete structures varied in each region, how the sample was composed, and how the data points of the different regions were positioned relative to the general trend, the sample was broken down by geographic location of the cases. In total, the data set was divided into four subsets: North America, Europe, Asia and Oceania. South America and Africa were not included due to the unavailability of data.

To begin with, Figure 11 displays the distribution of the embodied GHG emissions in the different regions. It might be noted that the sum of the cases of the four regions is different from the total number of reinforced concrete cases presented in Figure 4. The reason for this is that some cases had to be excluded because, instead of using specific data (emission coefficients) for their region, used external data from other regions. The subset that saw the biggest reduction in size due to this change was the North American one (10 less cases), followed by the Asian (4 less cases) and the European (1 less case) subsets. In the end, Europe became the subset with the majority of the observations, as only less than a third of the cases assessed with specific data were located in other regions.

Looking at the values of the embodied GHG emissions, it is visible that, in Asia, values reached fairly higher figures and varied slightly more than in Europe. Embodied GHG emissions in Asia ranged between 5.1 and 8.6 $kgCO_2$-eq/m^2.y and had an IQR of 3.4 $kgCO_2$-eq/m^2.y, whereas in Europe they varied between 2.9 and 5.0 $kgCO_2$-eq/m^2.y and had an IQR of 3.0 $kgCO_2$-eq/m^2.y. In Oceania, values varied even less and were between those of Europe and Asia, having an IQR of 1.6 $kgCO_2$-eq/m^2.y and ranging between 4.5 and 6.1 $kgCO_2$-eq/m^2.y; North America's subset only had one observation, and its carbon footprint was relatively high. Despite the difference in values between Europe, Asia and Oceania, all three distributions had a common feature: they were positively skewed.

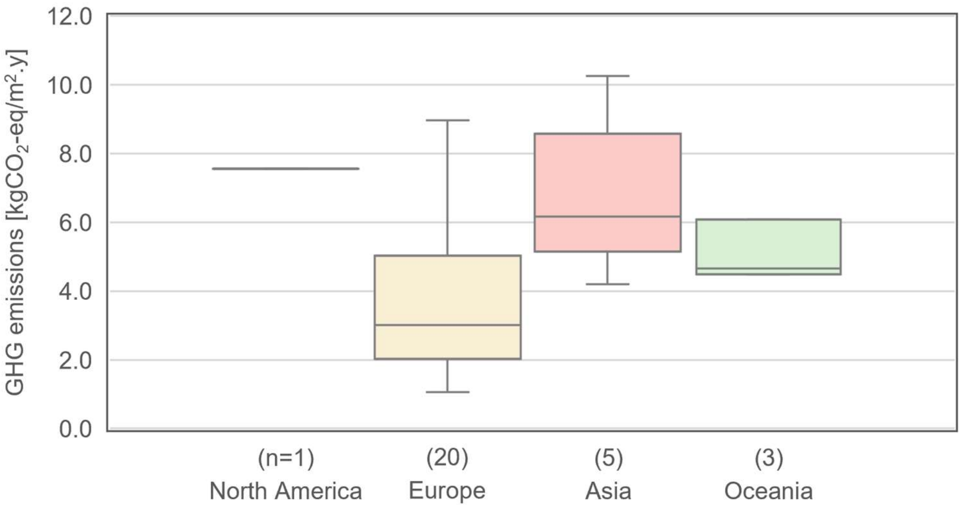

Figure 11. Box plot of the distribution of reinforced concrete buildings' embodied GHG emissions by geographic region.

Based on the arithmetic mean, European reinforced concrete buildings had a significantly lower average carbon footprint than that of buildings located in Asia and in Oceania, as illustrated in Figure 12.

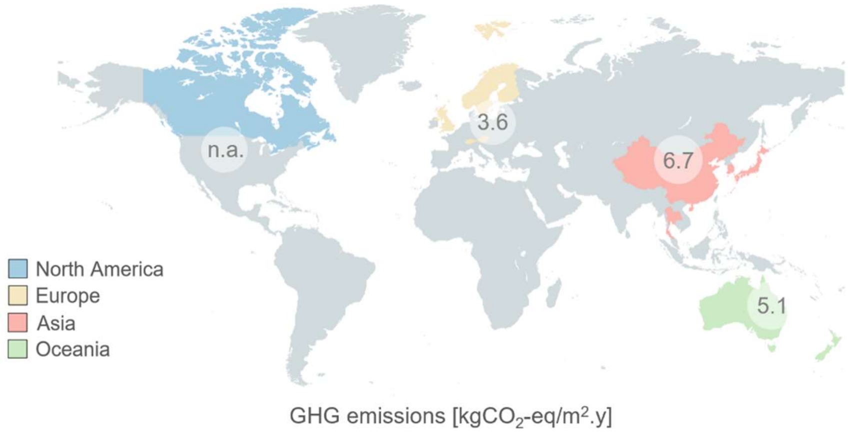

Figure 12. Average values of the embodied GHG emissions of reinforced concrete buildings by geographic region, with each region coloured to indicate the country of origin of the cases.

Figure 13 displays the embodied GHG emissions and the total number of floors of reinforced concrete buildings by geographic origin of the cases and the general model of reinforced concrete buildings, *RC (General)*, from Figure 6; the cases assessed with external data have also been plotted for comparison purposes. As can be noticed, the European sample was mainly composed of mid-rise buildings and all the reinforced concrete cases above 25 storeys were Asian. In addition, it is also possible to see that in Europe and Asia, embodied GHG emissions appeared to vary considerably regardless of the total number of floors of buildings. However, in Oceania, the values displayed a clear upward trend — similar to the general one of reinforced concrete buildings, but with higher values. The North American cases that were assessed with external data also appeared to exhibit an upward trend of the embodied GHG emissions — that was also similar to the general one, but had slightly lower values. In comparison with these cases, the only North American case that was estimated with specific data, had considerably higher embodied GHG emissions: with only five storeys, this case had the second highest carbon footprint of mid-rise buildings.

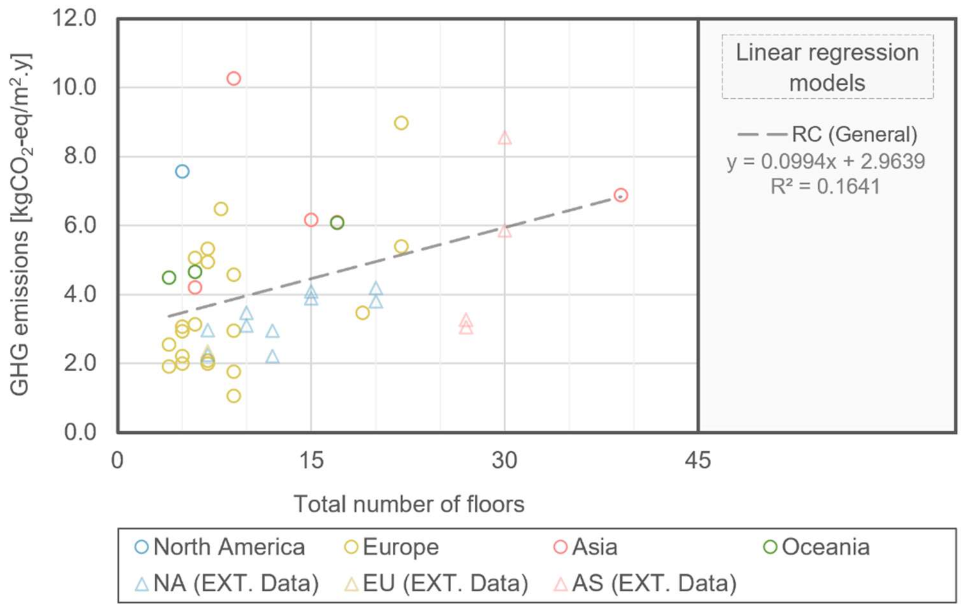

Figure 13. Scatter plot of reinforced concrete buildings' embodied GHG emissions as a function of the total number of floors by geographic region and linear regression model of reinforced concrete buildings.

Displayed in Figure 14 are the structural weight and total number of floors of reinforced concrete buildings by geographic region and the general linear regression model of reinforced concrete buildings, *RC (General)*, from Figure 8. Looking at the plot, it can be observed that the cases were grouped only in four subsets. Since the origin of the emissions factors was not relevant here (because the structural weight is not affected by them), all cases for which the structural weight was known were able to be included in their respective subset.

As can be seen, in Europe and Asia, the structural weight of buildings appeared to vary greatly in spite of the total number of floors (as it also happened in the analysis of the embodied GHG emissions). In North America, on the other hand, apart from one outlier (the same case that had a high carbon footprint), the cases seemed to display a similar upward trend to the general one of reinforced concrete buildings. Curiously, in Oceania, although the embodied GHG emissions appeared to exhibit an upward trend, the structural weight did not; the mass of structural materials of reinforced concrete buildings in Oceania seemed to remain relatively constant regardless of the total number of floors. In addition, it may also be noted that the case with a remarkably low structural weight was an Asian case.

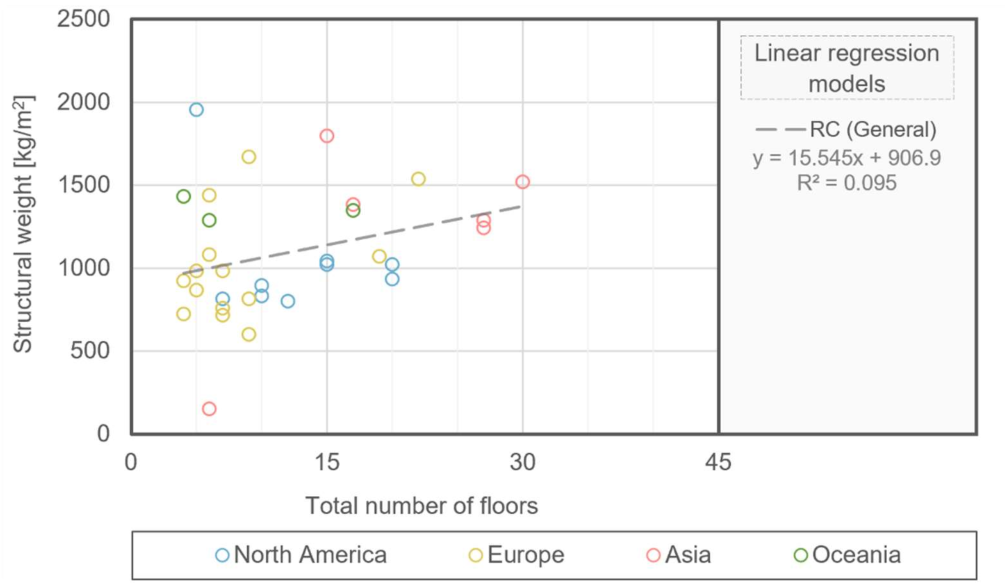

Figure 14. Scatter plot of reinforced concrete buildings' structural weight as a function of the total number of floors by geographic region and linear regression model of reinforced concrete buildings.

Analysing the embodied GHG emissions with the structural weight, plotted in Figure 15, despite the different geographic location of the cases, for the most part, values appeared to follow a common trend; yet there were still some differences between the values of the different subsets. For instance, the North American cases that were estimated with external data had similar structural weights to European buildings but had somewhat higher carbon footprints. In addition, in the same region, carbon footprint values also appeared to vary slightly (and in certain cases considerably) for the same structural weight.

Recalling the North American outlier, which stood out for having a noticeably high carbon footprint and structural weight for its height, and comparing its position relative to the general trend of reinforced concrete buildings, it can be noticed that it is in line with it. Given this, it may be concluded that its high carbon footprint (for its height) was mainly a result of a high structural weight.

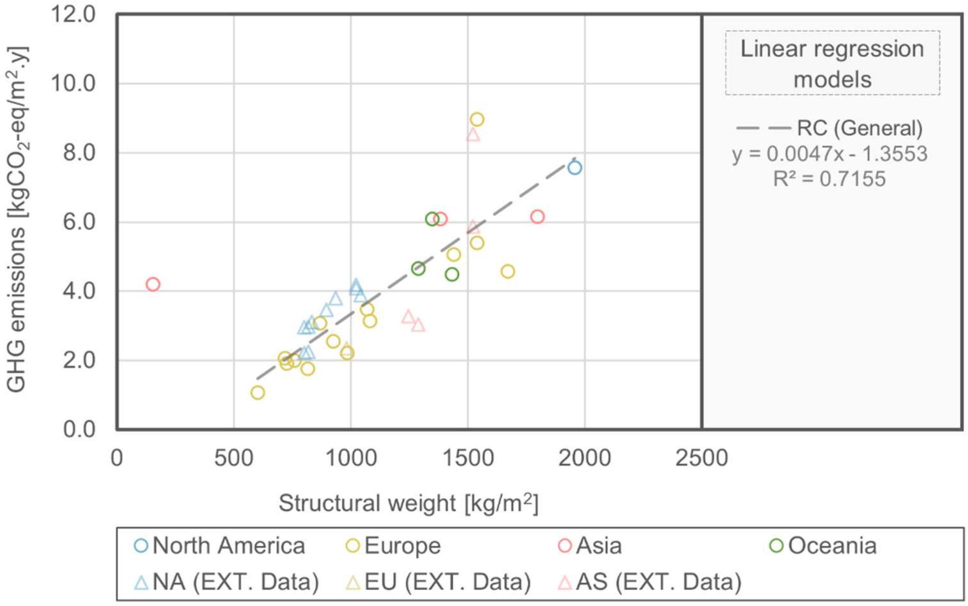

Figure 15. Reinforced concrete buildings' embodied GHG emissions and structural weight by geographic region.

Lastly, the average values (arithmetic mean without outliers) have been calculated for Europe, Asian and Oceania and represented in Figure 16; North America was omitted because it had only one case. The regions were represented by a point marked on the plot with the average carbon footprint of reinforced concrete buildings and their respective average structural weight; in addition, the average total number of storeys of the cases was also added to the plot to give a fuller picture of the subsets. It should be noted that these average values of embodied GHG emissions are not the same as the ones displayed in Figure 12, because not all cases had a corresponding value of structural weight associated with their carbon footprint, and thus not all were included in these calculations. As may be observed, the average values (of embodied GHG emissions and structural weight) also appear to follow an upward trend. Between the three regions, Asia was the one that had the highest average carbon footprint, structural weight and total number of storeys. Europe and Oceania had similar average values of the total number of storeys, but the former had a lower average carbon footprint and structural weight.

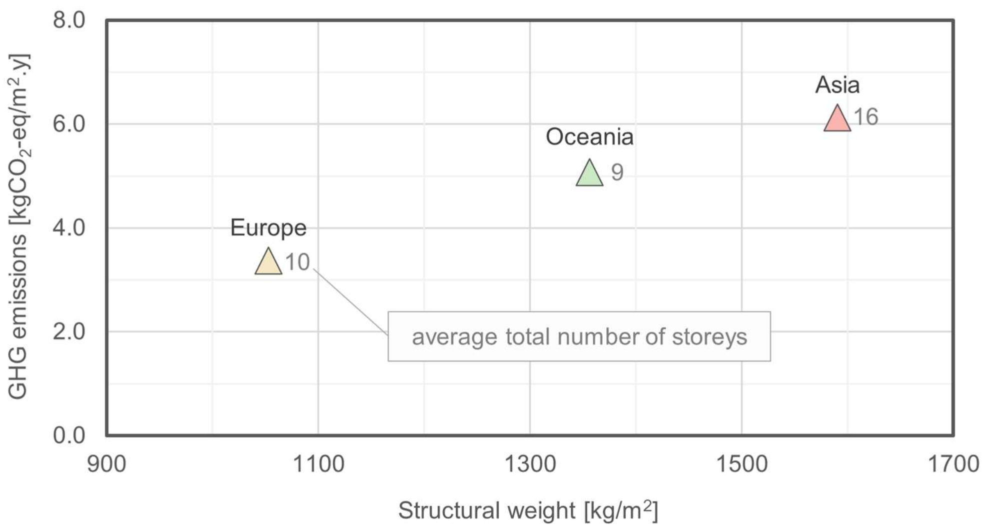

Figure 16. Average values of reinforced concrete buildings' embodied GHG emissions, structural weight and total number of storeys in each geographic region.

3.5.3 **Type of building use**

The design loads adopted in the design of a building's structure depend on the type of use that the building will have after its construction. Frequently, depending on the structural solution that is adopted, the increase of the design loads can lead to an increase of the structural weight. For instance, when the load capacity of a slab needs to be increased, a common solution adopted by structural engineers is to increase the thickness of the slab in order to increase its effective depth (i.e., the depth from the compression face of the slab to the centroid of the reinforcing steel in tension). This additional volume of concrete added to increase the thickness of the slab will result in an increase of the structural weight. Subsequently, with the increase of material quantities, the embodied GHG emissions will also rise. To understand if this difference between the values (of embodied GHG emission and of structural weight) of reinforced concrete buildings with different types of use was visible across buildings from distinct parts of the world and with distinct characteristics, the dataset was divided into six categories of use: residential, office, retail, hotel, educational, and mixed-use.

Figure 17 and Figure 18 present the distributions of the structural weight and embodied GHG emissions by building use, respectively. As might be noted, the structural weight of office buildings varied less than that of residential buildings, and the embodied GHG emissions varied in the same way in the two categories of use. Contrary to what would be expected, given that office buildings tend to have higher live loads than residential ones, the structural weights and embodied GHG emissions were very similar between the two types of use. As for the other categories, the few cases that composed them, in general, had higher values than those of residential and office buildings — with the exception of the case that had an extremely low structural weight.

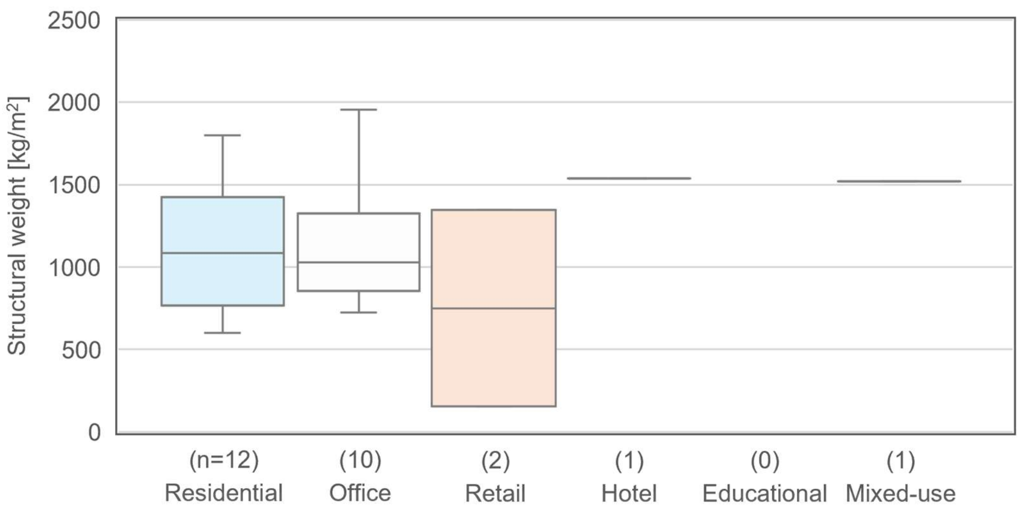

Figure 17. Box plot of the distributions of reinforced concrete buildings' structural weight by type of building use.

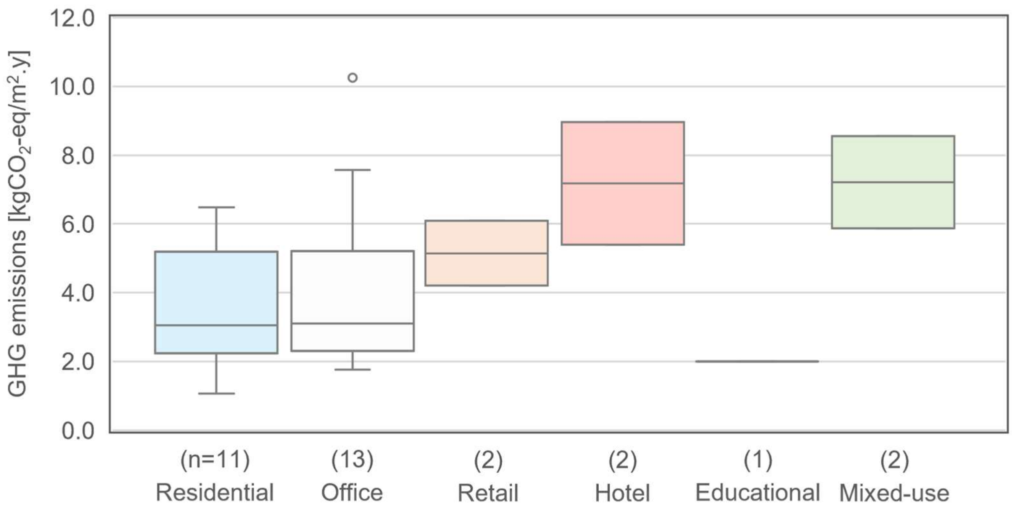

Figure 18. Box plot of the distributions of reinforced concrete buildings' embodied GHG emissions by type of building use.

Since building practices, codes and emission factors may differ from region to region, the six categories of use were broken down by region. The distributions of the structural weight of buildings by type of building use and by geographic region are represented in Figure 19. As can be seen, the majority of the subsets did not have a sufficient number of observations to allow for a sound comparison. The only categories of use that presented enough cases for their comparison were the residential and the office categories of European buildings (yet the variability of the values of residential buildings was relatively higher than that of office buildings). Looking at the European subsets of residential and office buildings, it is not possible to identify any clear difference between the values of the two types of buildings, as office buildings had a higher median, but residential buildings had higher maximum values.

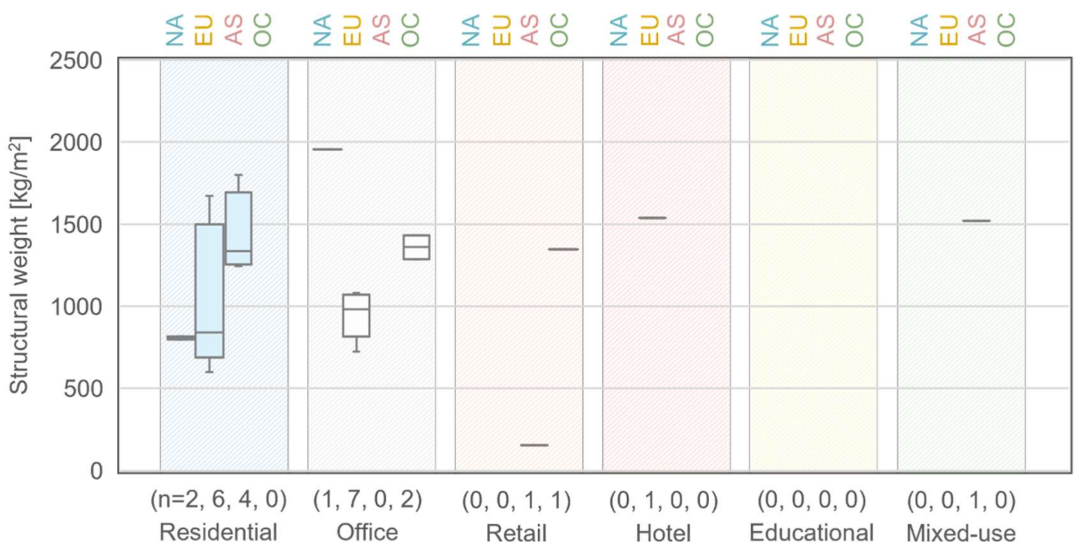

Figure 19. Box plot of the distribution of reinforced concrete buildings' structural weight by type of building use and by geographic region.

As for the embodied GHG emissions, the European subsets of residential and office buildings were, once again, the only subsets that had a sufficient number of cases to allow the comparison of the two types of building use, as shown in Figure 20. Here, European residential buildings not only had higher maximum values than those of office buildings but also had a higher median. Because this result is somewhat different from what was seen in the structural weight distributions — and since the previous data has suggested that the embodied GHG emissions and the structural weight are strongly related — it is not possible to draw any clear conclusions about the effect of the type of use of buildings, at a regional level, on the embodied GHG emissions or on the structural weight. However, it can be noticed that, within the same category of building use, values varied substantially from region to region — especially from Europe to Asia.

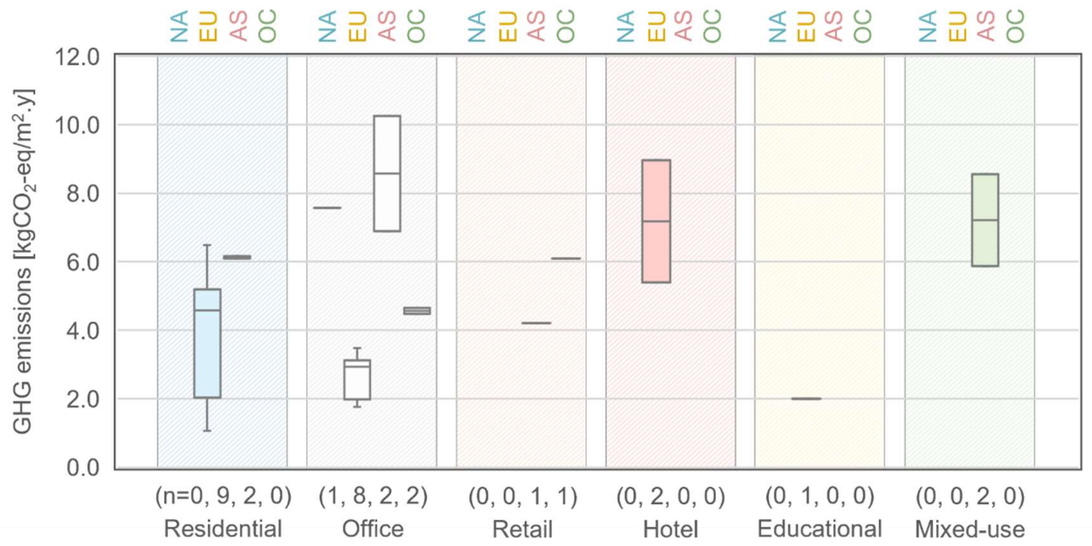

Figure 20. Box plot of the distribution of reinforced concrete buildings' embodied GHG emissions by type of building use and by geographic region.

3.5.4 **LCA approach: Input-output and process-based**

As was explained in Chapter 2 (section 2.2), input-output and process-based LCAs can yield significantly different estimates (Säynäjoki *et al*., 2017b). In order to assess if there was any general difference between their results, the meta-analysis sample was divided by type of LCA approach; the hybrid approach was not included because there were no cases assessed with this method. Figure 21 displays the number of cases in the sample assessed with each LCA approach over time. As can be seen, almost all cases were assessed with process-based LCAs. Only 2 of the 44 buildings had their carbon footprints quantified with an input-output approach (and they were both Asian).

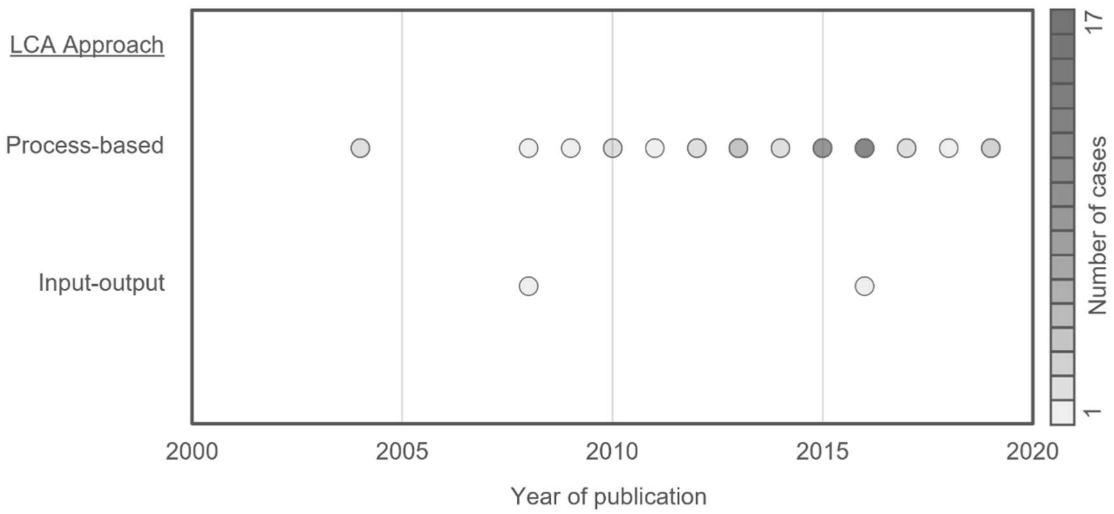

Figure 21. Distribution of the reinforced concrete cases through time by year of publication and by LCA approach.

As might be noticed in Figure 22, the two values estimated with input-output approaches were relatively high compared to the values of the process-based subset. In fact, one of these values was the highest of entire sample — and, as can be observed in Appendix A.2.1 (Figure A-1), it was substantially higher than those of the other cases with a similar total number of storeys.

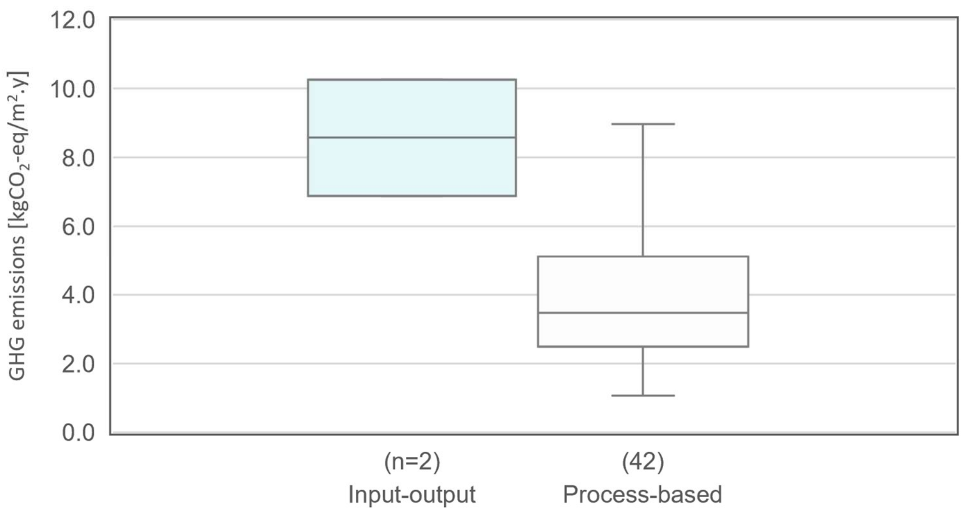

Figure 22. Box plot of the distribution of reinforced concrete buildings' embodied GHG emission by LCA approach.

3.5.5 **Relative mass of steel in buildings**

Previously, in section 3.5.1 (analysis of Figure 8), it was pointed out that one of the reinforced concrete cases stood out for having a remarkably low structural weight when compared with the values of the other cases. Additionally, in comparison with the other cases' carbon footprint, this case's value was rather high in proportion to its structural weight. After analysing its structural materials' quantities and comparing them with the values of some of the other cases, it was noticed that it had a strangely high quantity of steel in relation to its quantity of concrete (in terms of mass). In order to comprehend how the percentage of steel varies in reinforced concrete buildings, and how it affects their structural weight and carbon footprint, the relative quantity of steel (in terms of mass) has been plotted with the structural weight and with the embodied GHG emissions in Figure 23 and Figure 24, respectively.

In general, the percentage of steel in reinforced concrete buildings ranged from 3.5% to 6.4% (1^{st} and 3^{rd} quartile) and averaged 4.8% (based on the mean without the outlier). Observing Figure 23, it is possible to notice that the minimum values of the structural weight appear to remain relatively constant as the relative quantity of steel increases. Looking at the reinforced concrete outlier, we can see that it was fairly distanced from the other cases. The combination of this case's high percentage of steel with its exceptionally low structural weight seems to indicate that with the increase of the relative quantity of steel in buildings, the structural weight can suffer a decrease. Yet it should be noted, that, most likely, to reach higher percentages of steel — than what was observed in the majority of the reinforced concrete cases —, it is necessary to use composite frames of steel and concrete, as the quantity of reinforcement bars cannot be increased indefinitely due to the loss of ductility of the structures.

In an effort to compare the relative mass of steel of the outlier to that of steel-concrete composite frames and of steel frames, several cases have been added to the plots (Figure 23 and Figure 24). These cases stem from three studies comparing the carbon footprint associated with different types of structural systems (Trabucco *et al*., 2016; Nadoushani and Akbarnezhad, 2015a; Nadoushani and Akbarnezhad 2015b), yet it should be noted that the cases assessed by Trabucco *et al*. (2015) only include the buildings' superstructures (SS), and therefore their values could be slightly different from what would be estimated if the substructures had also been included. The higher scale representation of the entire plots can be found in Appendix A.2.2 (Figure A-2 and Figure A-3). As can be seen by the resemblance of the outlier with a steel-concrete composite case, it is possible that this case with an exceptionally low mass of structural materials per unit floor area, that was first presumed to be a reinforced concrete case (based on the information provided by the study), is actually a steel-concrete composite frame. Because of this, it will not be included in the sample that will be used in the following chapter for the benchmark comparison and definition.

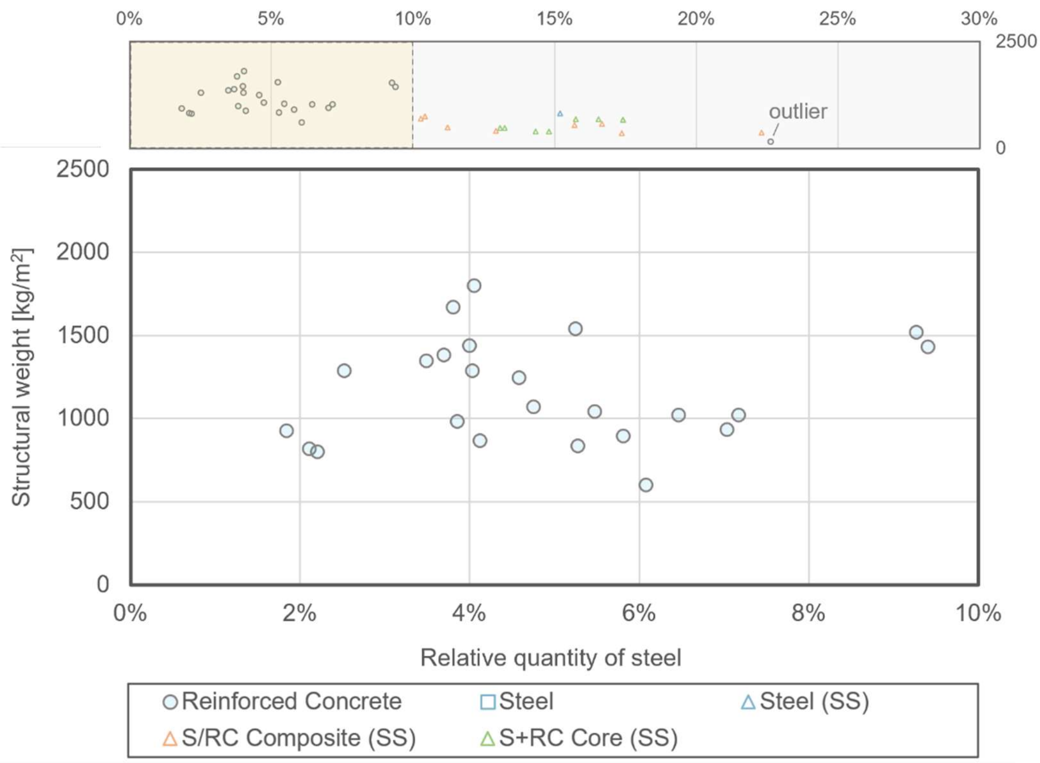

Figure 23. Scatter plot of reinforced concrete buildings' structural weight as a function of the relative quantity of steel.

What was strange about this case, was not just its extremely low structural weight but also the value of its carbon footprint. Despite this case's low structural weight, its carbon footprint was only similar to those of reinforced concrete buildings with a structural weight above 1,000 kg/m^2. Looking at the embodied GHG emission of reinforced concrete buildings in relation to the quantity of steel, presented in Figure 24, the low structural weight values of reinforced concrete buildings appear to increase as the percentage of steel increases, yet the high values seem to vary independently of the relative quantity of steel. In contrast to Figure 23, where the structural weight of reinforced concrete buildings was in general higher than that of steel-concrete composite buildings and of steel buildings, here the values seem to be fairly similar. Overall, although using a high percentage of steel seems to enable buildings to have a much lower structural weight, it does not appear to result in a reduction of the carbon footprint, as buildings with higher percentages of steel tend to have higher carbon footprints for their structural weight — due to the higher emission coefficients of steel in relation to those of concrete (virgin steel emission coefficients can be more than 10 times higher than those of concrete; Pomponi and Moncaster, 2018). This becomes especially evident when the embodied GHG emissions are plotted with the structural weight, as presented in Appendix A.2.2 (Figure A-4). Furthermore, the results from Nadoushani and Akbarnezhad (2015a; 2015b) and Trabucco *et al*. (2016) indicate that the carbon footprints of steel-concrete composite frames and of steel frames are very similar to that of reinforced concrete buildings (for the same total number of storeys), as shown in Appendix A.2.2 (Figure A-5 and Figure A-6).

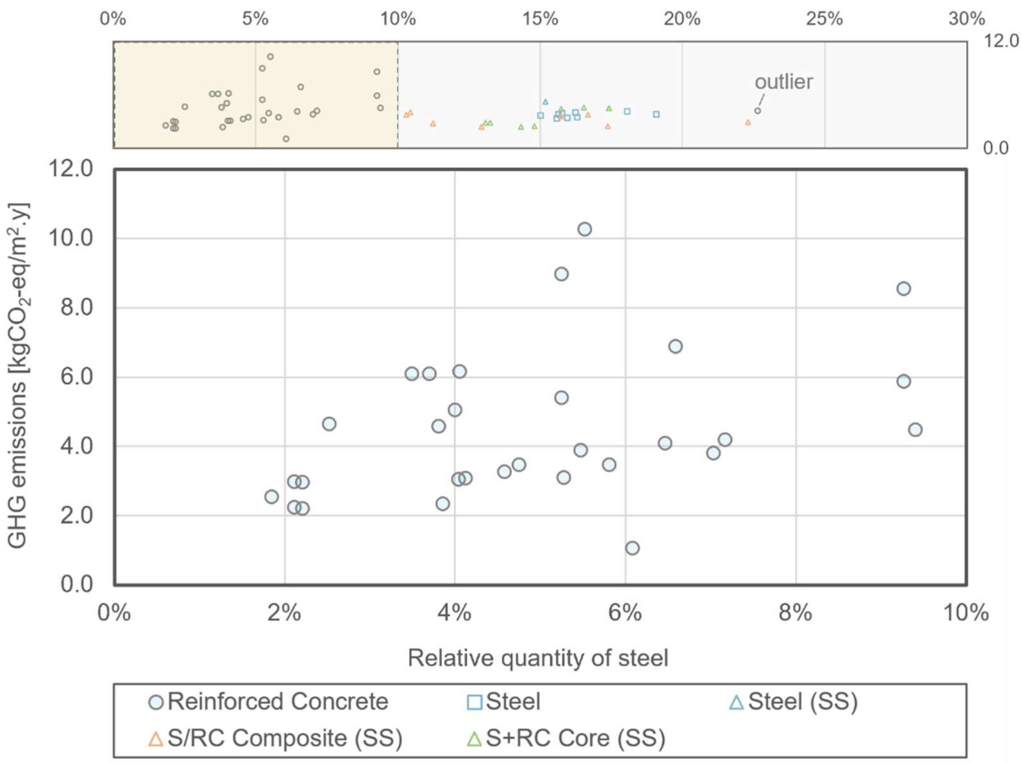

Figure 24. Scatter plot of reinforced concrete buildings' embodied GHG emissions as a function of the relative quantity of steel.

Chapter 4

Benchmarks for the embodied GHG emissions

Buildings' operation used to be the largest contributor to their carbon footprint. However, due to efforts in the last decades to minimize operational GHG emissions, by improving the energy efficiency of buildings (either by having more energy efficient appliances, with low energy consumptions, or by reducing the need for heating and cooling by having better insulated buildings), today their absolute and relative contributions have been successfully lowered. As a result, the relative share of embodied GHG emissions has increased, to the point that, in some cases, it equals or even surpasses operational emissions (Röck *et al.*, 2020b).

One of the key actions that has led to this effective reduction of operational 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 target values established, known as benchmarks. Benchmarks 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 (e.g., infrastructure, buildings, mobility and food) and sub-sectors (e.g., residential, offices, schools, hotels, restaurants), 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 (and usually consider the best performing cases).

Today, several benchmarking systems for buildings' environmental impacts have already been (or are planned to be) introduced in various European countries (namely in France, Switzerland, Belgium, Denmark, Czech Republic, Germany and the Netherlands) (Frischknecht *et al.*, 2019; Trigaux *et al.*, 2021). One of them is specified in SIA 2040 Energy Efficiency Path (SIA, 2011): a Swiss technical specification that defines target values based on the Swiss 2000-Watt Society model. In this model, the annual primary energy consumption and annual GHG emissions are reduced, respectively, to 2,000 watts per capita and 1 tCO_2-eq per capita (for all activities in a person's life). Its underlying principle is that those figures are assumed to be both environmentally sustainable and sufficient to ensure a good quality of life. Originally, these targets were set to be achieved by 2150, but to comply with the Paris Agreement requirements and limit global warming to 1.5 ºC the deadline has been brought forward to 2050 and the GHG emission target has been reduced to net-zero (EnergieSchweiz für Gemeinden *et* *al.*, 2014; EnergieSchweiz für Gemeinden and Fachstelle 2000-Watt-Gesellschaft, 2020; FOEN, 2021). The Swiss Energy Efficiency Path, however, 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 (based on historical data of the origin of the emissions); 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). Table 5 displays the SIA 2040 benchmarks of the embodied, operational and life cycle GHG emissions for the various types of buildings.

Table 5
SIA 2040 benchmarks for buildings (SIA, 2017a, 2017b).

Type of building	GHG emissions ($kgCO_2$-eq/m^2ERA.y)		
	Embodied	Operational	Total
Residential	9.0	3.0	12.0
Office	9.0	4.0	13.0
School	9.0	2.0	11.0
Grocery store	9.0	29.0	38.0
Specialty store	9.0	5.9	14.0
Restaurant	9.0	10.0	19.0

4.1 Benchmark comparison

Due to its simplistic approach, SIA 2040's benchmarks have already been used in some studies as a basis for comparison (Röck *et al.*, 2020b; Hoxha *et al.*, 2016). In order to assess the importance of the values of the embodied GHG emissions of structural frames in complying with carbon budgets, and consequently successfully mitigating climate change, 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 was also applied — according to SIA 380, the energy reference area excludes non-heated areas such as garages, technical rooms, storage rooms and laundry rooms, but includes corridors, staircases, sanitary spaces and closets (SIA, 2015). The adopted conversion factor, 0.9, was based on the GFA-to-ERA ratio used in SIA 2040 (Jakob *et al.*, 2016). The adapted benchmarks per m^2 GFA, derived from the 2050 target of 1 tCO_2-eq per capita, are given by Equation *(*2) and are presented in Table 6.

$$Budget_{1\ tCO_2-eq\ 2050} = \frac{Budget_{SIA\ 2040}}{2} \times f_{ERA-to-GFA} \tag{3}$$

Table 6
Variation of SIA 2040's benchmarks for buildings per m^2 GFA, based on a target of 1 tCO_2-eq per capita by 2050.

Type of building	GHG emissions ($kgCO_2$-eq/m^2GFA.y)		
	Embodied	Operational	Total
Residential	4.1	1.4	5.4
Office	4.1	1.8	5.9
School	4.1	0.9	5.0
Grocery store	4.1	13.1	17.1
Specialty store	4.1	2.7	6.7
Restaurant	4.1	4.5	8.6

Figure 25 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, and a few even exceeded the benchmark for the entire life cycle of residential and office buildings, 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 and life stages of the buildings, less than 2 $kgCO_2$-eq/m^2.y. Timber buildings, on the other hand, had a reasonable embodied emissions surplus, in general more than half of the embodied emissions budget. In some of the timber buildings in which the effect of CO_2 sequestration was accounted for, the remaining budget was even higher than the initial one, due to a negative carbon footprint of the structural system. On average, reinforced concrete buildings failed to meet the benchmark by 0.1 $kgCO_2$-eq/m^2.y, whereas timber buildings, after the production of the structural frames' materials, still had a budget surplus of 2.6 $kgCO_2$-eq/m^2.y; if the effect of CO_2 sequestration was included, this number would increase to 3.7 $kgCO_2$-eq/m^2.y.

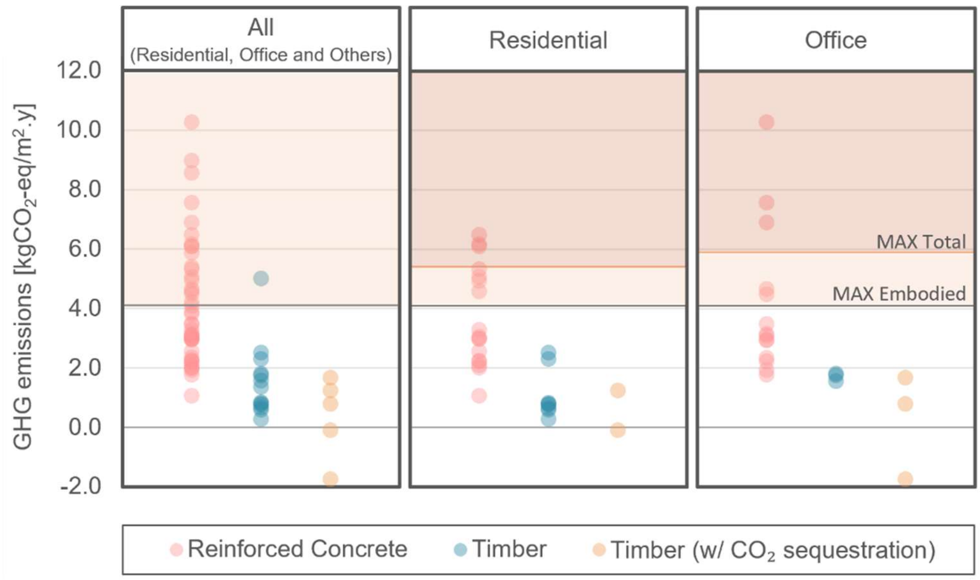

Figure 25. Structural frames' embodied GHG emissions benchmark comparison.

If we now compare the actual difference between using reinforced concrete and timber on a building, by comparing the cases of buildings that were designed with the two alternatives, as Figure 26 shows, for some of the buildings, opting for a timber design made the difference between meeting or not meeting the target value for embodied emissions. In the cases where both designs were able to meet the benchmark, the timber alternatives enabled to have a larger remaining budget for the other elements and life cycle stages of buildings, increasing the chances of the complete building complying with the budget. The difference between choosing a reinforced concrete design or a timber design was, on average, 2.0 $kgCO_2$-eq/m^2.y, yet with the inclusion CO_2 sequestration it increased to 5.8 $kgCO_2$-eq/m^2.y The actual values of these cases can be found in Appendix A.1 (Table A-2).

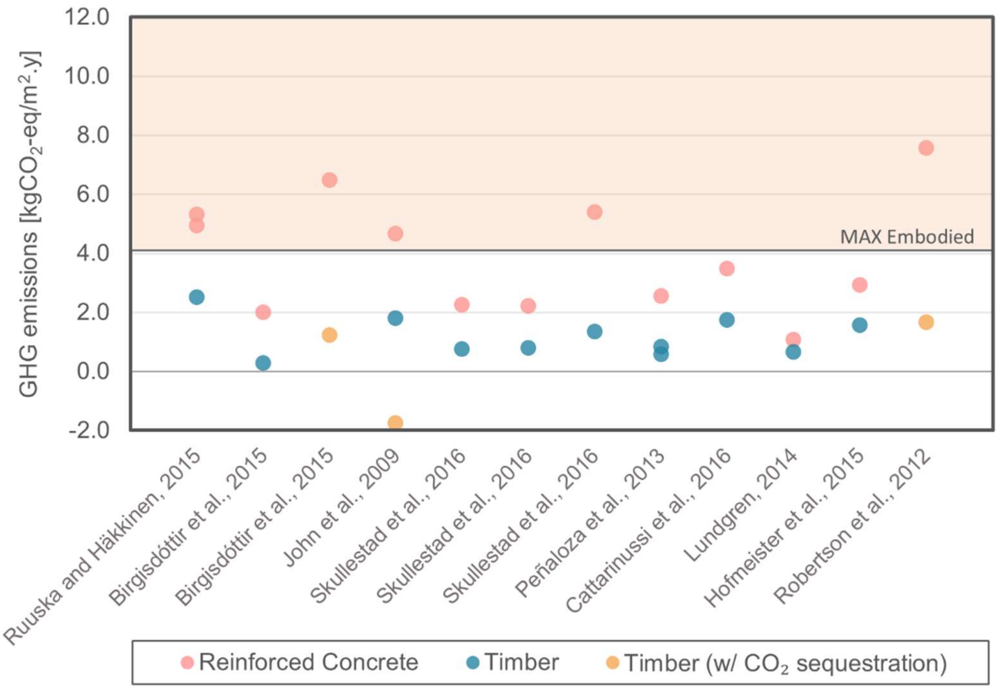

Figure 26. Benchmark comparison of the two design alternatives (reinforced concrete and timber) for the same building.

It should be mentioned that the effect of carbonation in concrete was not considered because it is attributed to the use phase, moreover, most of the studies did not take it into account. Yet based on the few that did, accounting for it can lead to a reduction of the embodied GHG emissions in reinforced concrete buildings of about 0.2 and 0.3 $kgCO_2$-eq/m^2.y. In timber buildings, that reduction does not seem to go beyond 0.1 $kgCO_2$-eq/m^2.y due to the lower quantity of concrete (Skullestad *et al.*, 2016; Peñaloza *et al.*, 2013; Lundgren, 2014).

4.2 Benchmark definition

A building's structural system usually composes most of the building's mass, and (due to the large material quantities) can be one of the main contributors to the embodied share of emissions (Wallhagen *et al.*, 2011; Dokka *et al.*, 2013). As a consequence, its impact can dictate the success of meeting GHG emissions targets, as it was shown in section 4.1. It is therefore of upmost importance that the carbon footprint of buildings' structures starts being assessed, and considered, from the very beginning of the building design, but for that it is first necessary that reference and target values are available for comparison.

Though several benchmarks for buildings have already been established based on LCAs' results (i.e., with a bottom-up approach), and at the structure level De Wolf *et al*. (2020) has even developed a database (deQo) with LCA results to enable practitioners to have a better understanding of the range of values in which material quantities and embodied GHG emissions of structures vary, there are yet to be laid down clear target values (Hollberg *et al*., 2019; Trigaux *et al*., 2021).

In this sense, using the meta-analysis data set, reference and target values for reinforced concrete and timber structures (including substructure and superstructure) were defined, based on models of the data; the effect of biogenic CO_2 sequestration was decided to not be considered because there were not enough cases and also because different accounting methods can lead to different estimates (Hoxha *et al*., 2020). The purpose of these models was to smooth the empirical distributions. 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). The source code (Figure A-7) and outputs of the created program may be found in Appendix A.2.3.

Initially, the distributions were selected from a group of candidates that were chosen by observing the empirical plots of the data (Figure A-8 and Figure A-15); since the empirical distributions (of the reinforced concrete sample and timber sample) were positively skewed, the gamma, lognormal and Weibull distributions were considered — this decision was also in line with what the skewness-kurtosis plots (or Cullen and Frey graphs) indicated (Figure A-9 and Figure A-16), as can be seen by the closeness of the observations to the values of the theoretical distributions (note that some theoretical distributions have numerous possible values, and thus they are represented by a line or an area) (Delignette-Muller and Dutang, 2015). With the distributions chosen, the values of the parameters were estimated with the maximum likelihood estimate method (by maximizing the likelihood of observing that data) 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 (Figure A-10 and Figure A-17) and the theoretical cumulative distribution functions (CDFs) to the empirical one (Figure A-11 and Figure A-18); it also included the analysis of the quantile-quantile (Q-Q) plot (Figure A-12 and Figure A-19) and probability-probability (P-P) plot (Figure A-13 and Figure A-20) to further understand the goodness-of-fit at the tails and centre of the distributions, respectively (Delignette-Muller and Dutang, 2015). In a Q-Q plot the quantiles of the theoretical distribution are plotted against the quantiles of the empirical distribution, in a P-P plot the theoretical CDF is plotted against the empirical CDF; if the theoretical distribution fits the data reasonably well, the two plots should resemble an identity function. In addition to the visual assessment, a statistical assessment was also performed (Figure A-14 and Figure A-21), by comparing goodness-of-fit statistics, namely the Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling statistics, between the candidate distribution; since these statistics measure the discrepancy between the theoretical distributions and the data, the distribution that was considered to be the best fit was the one that minimized them. When the candidate distributions have different numbers of parameters, it is common to take the complexity of the models also into account, by comparing goodness-of-fit criteria such as the Akaike's information criterion (AIC) and the Bayesian information criterion (BIC) (Delignette-Muller and Dutang, 2015), but in this case the number of parameters was common among all distributions (two).

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 — but the one of timber buildings had a worse fit than that of reinforced concrete buildings, possibly due to the lower number of observations. This was also supported by the statistical assessment, given that all the goodness-of-fit statistics favoured the log-normal distributions. As noted above, the goodness-of-fit criteria were not as relevant in this case because all the distributions were characterized by two parameters, nonetheless they also indicated that the log-normal distribution was the best approximation. Considering this, it was decided to model the reinforced concrete buildings data and the timber buildings data with the log-normal distributions displayed in Figure 27 — this is not the first time that a log-normal distribution has been used to model data in LCA studies (Chau *et al*., 2012; Hart *et al*., 2021; Heijungs and Frischknecht, 2005; Hollberg *et al*., 2019).

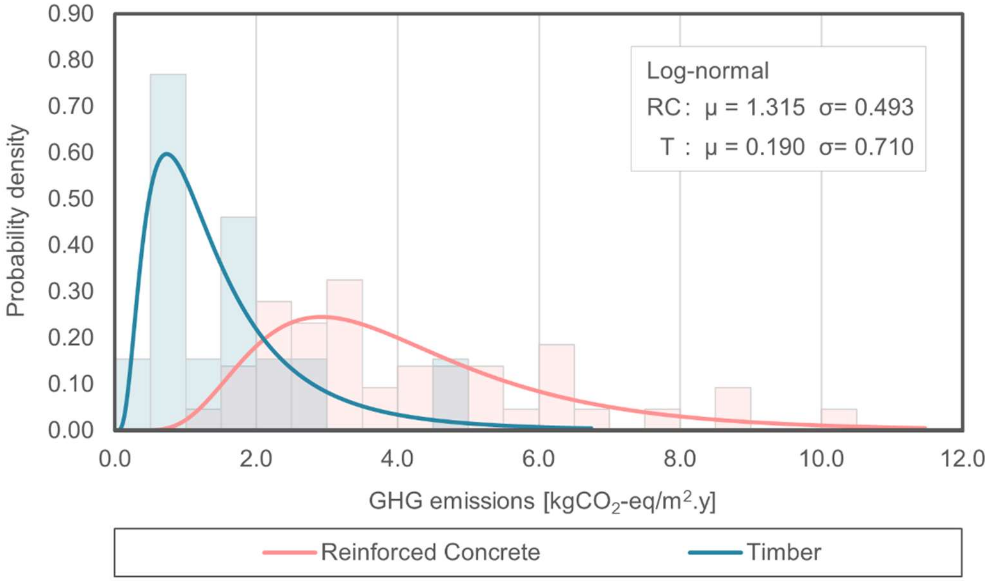

Figure 27. Empirical histograms and fitted log-normal distributions of reinforced concrete buildings and timber buildings.

The reference and target values for reinforced concrete structures and timber structures were established based on the same definition that was used for the European SuPerBuildings Project (Häkkinen, 2012): the reference values represent the current practice, and thus correspond to the median values (50th percentile), and the target values identify the highest level of performance currently achievable, which in this study was considered to be the 5th percentile of the distributions (i.e., the value that, theoretically, was not exceeded by only 5% of the buildings).

Table 7 presents the theoretical reference and target values for reinforced concrete structures and for timber structures: the empirical values (corresponding to the percentiles of the data sets) are also displayed for comparison purposes. Looking at the figures, in general, the values estimated from the fitted distributions were more conservative than the ones calculated from the data sets. The visualization of the difference between the empirical and theoretical percentiles can be observed in Appendix A.2.3 (Figure A-22 and Figure A-23).

Table 7
Theoretical and empirical reference and target values for reinforced concrete structures and timber structures.

Type of structure	GHG emissions ($kgCO_2$-eq/m^2.y)			
	Reference value		Target value	
	Empirical	Theoretical	Empirical	Theoretical
Reinforced concrete	3.5	**3.7**	1.9	**1.7**
Timber	1.3	**1.2**	0.5	**0.4**

Figure 28 combines the reference and target values defined and the top-down benchmark adapted from SIA 2040 for embodied emissions. 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.

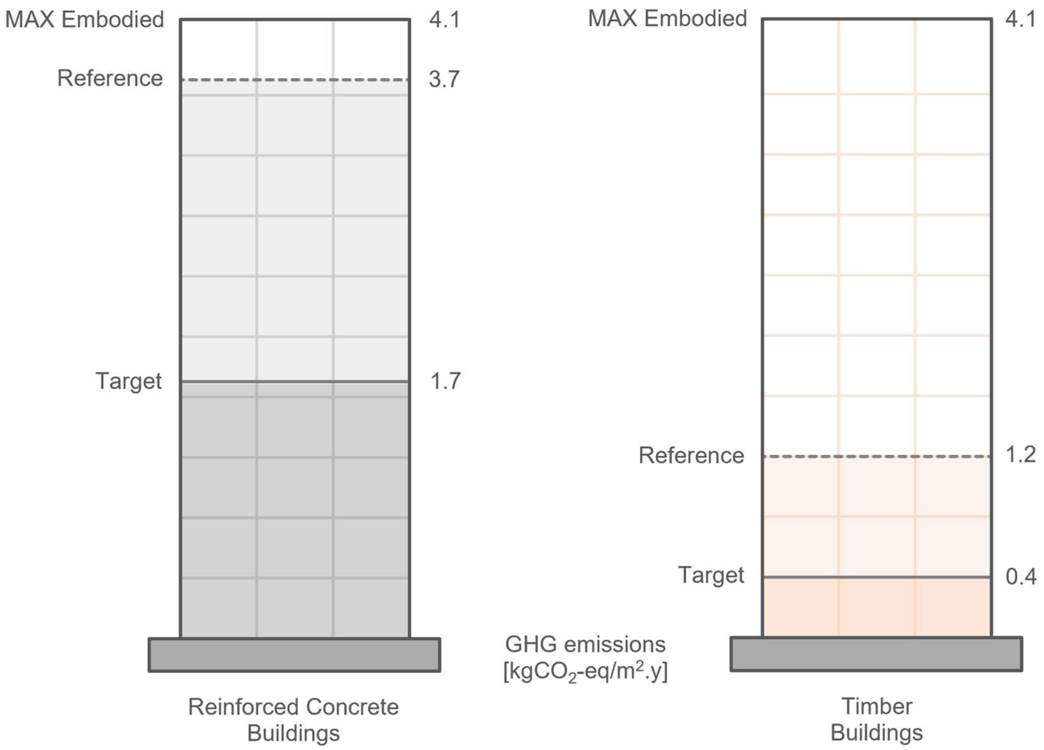

Figure 28. Benchmarks for reinforced concrete and timber buildings' structures.

4.3 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. Chau *et al*. (2012) suggested creating a classification system by dividing a fitted distribution, of embodied GHG emissions in reinforced concrete office buildings, into performance bands (e.g., A, B, C, D, E and F). Yet that system would not enable a direct comparison between different structures, because, as was mentioned in section 4.2, even the best performing reinforced concrete buildings (at target level) had a higher GWP than the average timber building (at reference level). Furthermore, such a system could overlook climate targets, as it does not consider them. For that reason, it seems that a common classification system, created with a top-down approach, 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.

Bearing in mind how much of the embodied budget for buildings (resulting from a per capita budget of 1 tCO_2-eq by 2050) is consumed by the structure and the ranges in which values vary (for reinforced concrete and timber buildings), a 'carbon' labelling system was designed to classify the environmental performance, in terms of GWP, 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. For example, the definition of the A class took into account the carbon footprint of the best performing structures (i.e., the timber structures that meet the target value of 0.4 $kgCO_2$-eq/m^2.y) and the fact that values can go below zero if biogenic CO_2 sequestration is accounted for in timber structures — an alternative approach would be to create another class for buildings with a negative carbon footprint. The actual class boundaries (in $kgCO_2$-eq/m^2.y) can be found in Figure 29, where the suggested 'carbon' label is represented.

As can be noted the proposed design is fairly similar to that of energy efficiency labels and energy performance certificates (BPIE, 2014; European Comission, 2021b), but with the difference that it has a different colour scheme, in order to make it distinguishable. The classes with a low performance (i.e., a higher GWP) are characterized by dark grey colours and the classes with a high performance (i.e., lower impact) are characterized by blue tones.

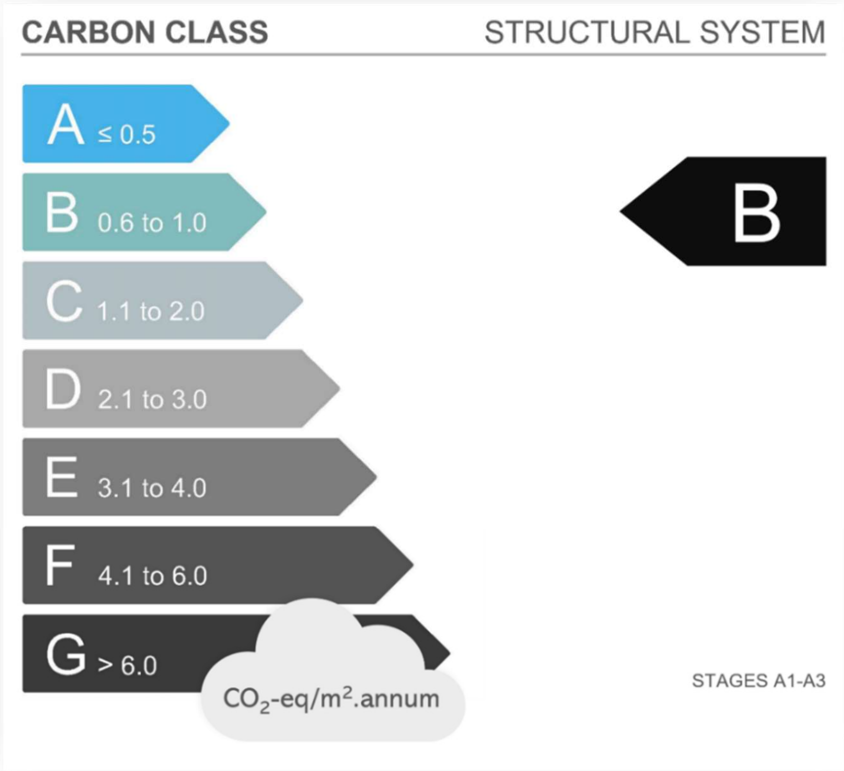

Figure 29. Example of the suggested carbon label for a building's structure classified with a B.

To exemplify how this label can provide a clearer sense of the environmental performance of buildings in terms of GWP, the cases from the meta-analysis sample have been classified and the results are presented in Table 8. In general, reinforced concrete buildings ranged from class D to G and their best performance was rated a C. Timber buildings, in contrast, were mostly in the B and C categories and their best and worst performance were, respectively, labelled an A and a F. According to the cases displayed in Figure 26, using a timber structure instead of a reinforced concrete one can lead to an increase of the building performance, on average, of two classes, and, in extreme cases, of five classes (when CO_2 sequestration is considered).

Table 8
Classification of the cases from the meta-analysis sample with the suggested labelling system.

Type of structure	Carbon Class						
	A	B	C	D	E	F	G
Reinforced Concrete	0	0	5	11	8	10	9
Timber	3	6	6	2	0	1	0

All things considered, although it would be ideal to have a labelling system covering the whole life cycle of buildings and all their components, the suggested classification for structural systems seems to be a useful starting point for informing stakeholders in the real estate sector (e.g., investors, owners, occupiers and promoters) about the climate change impact of buildings.

Chapter 5

Discussion and conclusions

5.1 Discussion

5.1.1 **Meta-analysis results**

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 Chapter 2 (section 2.1), 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) (Luo *et al*., 2016; Skullestad *et al*., 2016; Hart *et al*., 2021; Nadoushani and Akbarnezhad, 2015a).

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. However, if the effect of biogenic CO_2 is considered in the LCA of timber buildings, carbon emissions from material production reduce, but maintain a similar rate of increase. Based on the linear regression models, including the benefits of sequestered CO_2 in timber structures results in a reduction of the carbon footprint of about 3 $kgCO_2$-eq/m^2.y (for the same structural weight) and leads structures with quantities of structural materials below ~750 kg/m^2 to have a negative GWP, i.e., causing a net decrease in atmospheric CO_2 concentration. 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. De Wolf *et al*. (2015), also assessed the embodied GHG emissions and structural weight by type of buildings use and found, between residential and office buildings, embodied GHG emissions to be slightly higher and quantities of structural materials to vary more in buildings with a residential use. Säynäjoki *et al.* (2017b) compared the results of process-based and input-output LCA and the results suggested that the two approached produce significantly different results, with the input-output assessment estimating a value almost twice as high as that of the process-based.

5.1.2 **Benchmarks for structures**

The comparison of the cases to a variation of the Swiss SIA 2040 benchmark, that was based on an 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 structures leave 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 components and life cycle stages. 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 Chapter 3 (Figure 6) 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 an appropriate 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.

5.2 Conclusions

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 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 a large part of the budget for embodied emissions, leaving only 60% of the budget for the remaining life cycle stages and building components. It should be noted, 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 also be considered (Cattarinussi *et al*., 2016; Hart *et al*., 2021; Skullestad *et al*., 2016).

5.3 Future work

Taking into consideration the aspects that this thesis was not able to address, the following paths are open for exploration:

- Analyse the influence of factors with a more comprehensive sample, that has cases more evenly distributed across the different subsets;
- Replicate the method used to determine the reference and target values and performance classes in a more complete data set and extend the benchmarks to other life cycle stages;
- Determine reference and target values for other common structural systems used in mid- and high-rise construction, namely steel and steel-concrete composite structures.

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Appendix A

Additional contents

A.1 Tables

Table A-1
Geographic distribution of the final sample, detailing the number of cases by country.

Structural material	Geographic location	Number of cases	
Reinforced Concrete	**North America**	**11**	
	Canada		1
	United States		10
	Europe	**21**	
	United Kingdom		1
	Norway		7
	Sweden		6
	Finland		4
	Switzerland		1
	Austria		1
	Greece		1
	Asia	**9**	
	China		5
	South Korea		1
	Japan		1
	Thailand		1
	Singapore		1
	Oceania	**3**	
	Australia		2
	New Zealand		1
Timber	**North America**	**2**	
	United States		2
	Europe	**10**	
	United Kingdom		1
	Norway		3
	Sweden		4
	Finland		1
	Switzerland		1
	Oceania	**1**	
	New Zealand		1
Timber (w/ CO_2 sequestration)	**North America**	**1**	
	Canada		1
	Europe	**3**	
	United Kingdom		1
	Austria		1
	Spain		1
	Oceania	**1**	
	New Zealand		1

Table A-2
Embodied GHG emissions of reinforced concrete and timber designs of the same building.

Study	Embodied GHG emissions ($kgCO_2$-eq/m^2.y)			Timber system
	RC	T	Reduction	
Birgisdóttir *et al.*, 2016	2.0	0.3	-1.7	N/A
Ruuska and Häkkinen, 2015	5.3 and 4.9	2.5	-2.8 and -2.4	Light-frame
John *et al.*, 2009	4.7	1.8	-2.9	LVL + Timber-concrete slabs
Skullestad *et al.*, 2016	2.2	0.8	-1.5	Glulam + CLT
Skullestad *et al.*, 2016	2.2	0.8	-1.4	Glulam + CLT
Skullestad *et al.*, 2016	5.4	1.3	-4.1	Glulam + CLT
Peñaloza *et al.*, 2013	2.5	0.8	-1.7	LVL + Glulam
		0.6	-2.0	CLT
Cattarinussi *et al.*, 2016	3.5	1.7	-1.7	Post-tensioned Glulam
Lundgren, 2014	1.1	0.7	-0.4	Glulam + CLT
Hofmeister *et al.*, 2015	2.9	1.6	-1.4	Glulam
With CO_2 sequestration				
Birgisdóttir *et al.*, 2016	6.5	1.2	-5.2	CLT
Robertson, 2011	7.6	1.7	-5.9	Glulam + CLT
John *et al.*, 2009	4.7	-1.7	-6.4	LVL + Timber-concrete slabs

A.2 Charts and figures

A.2.1 **LCA approach: Input-output and process-based**

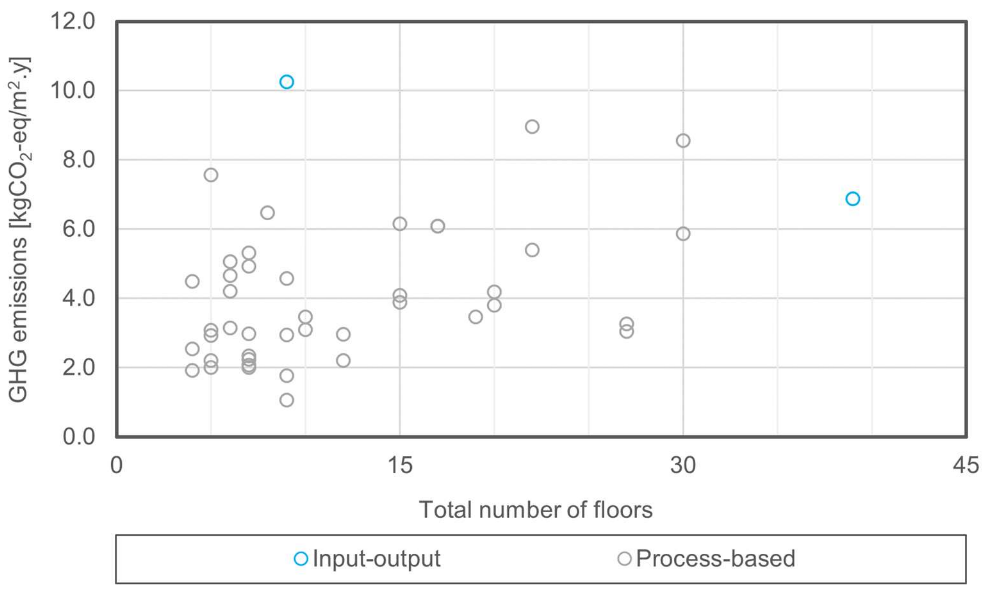

Figure A-1. Scatter plot of reinforced concrete buildings' embodied GHG emissions as a function of the total number of floors by type of LCA approach.

A.2.2 **Relative mass of steel in buildings**

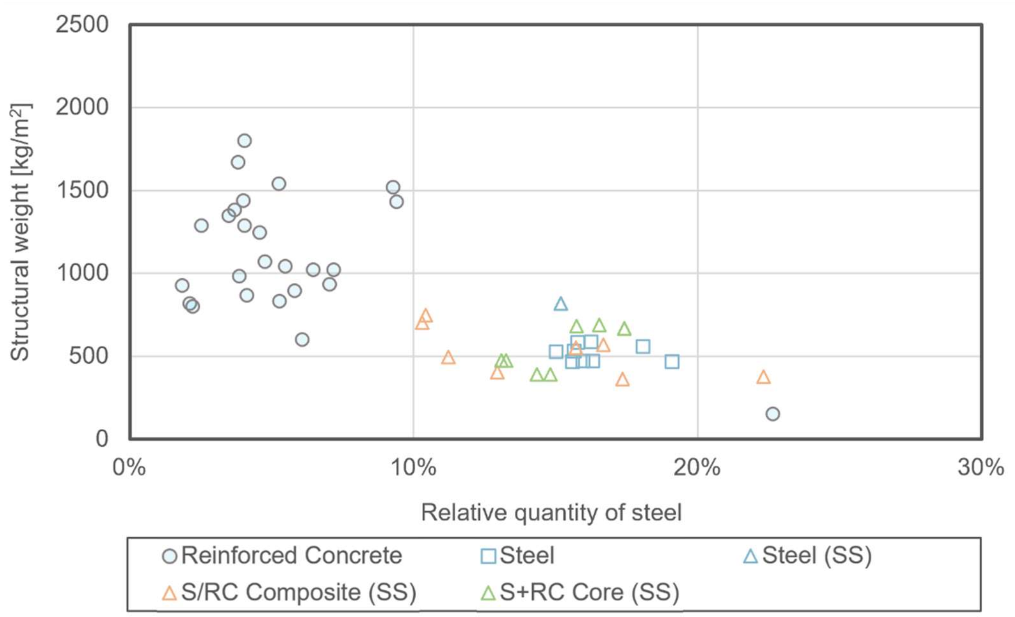

Figure A-2. Higher scale scatter plot of reinforced concrete buildings' structural weight as a function of the relative quantity of steel by type of structural system.

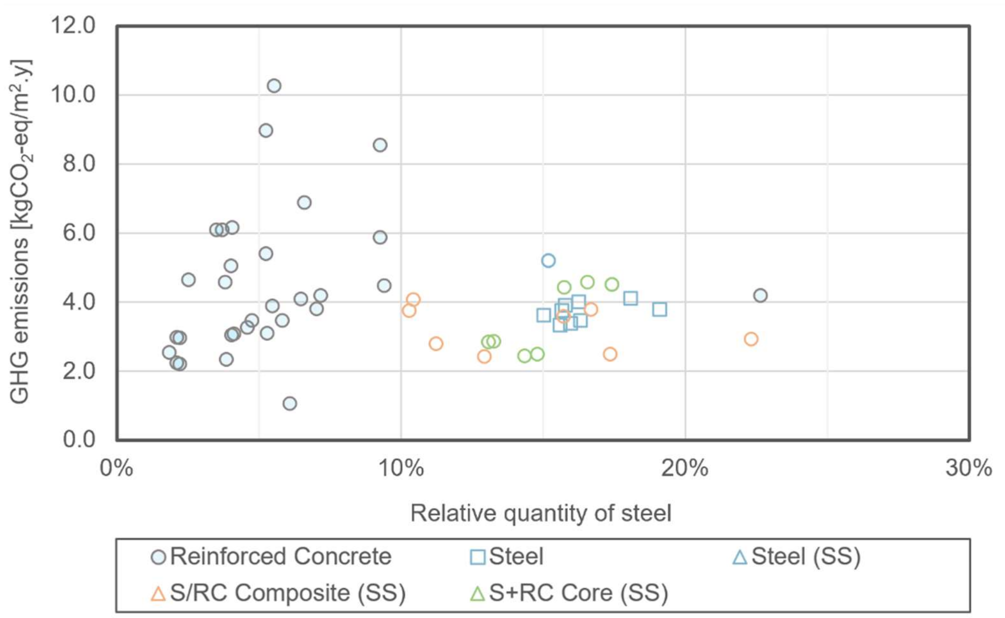

Figure A-3. Higher scale scatter plot of reinforced concrete buildings' embodied GHG emissions as a function of the relative quantity of steel by type of structural system.

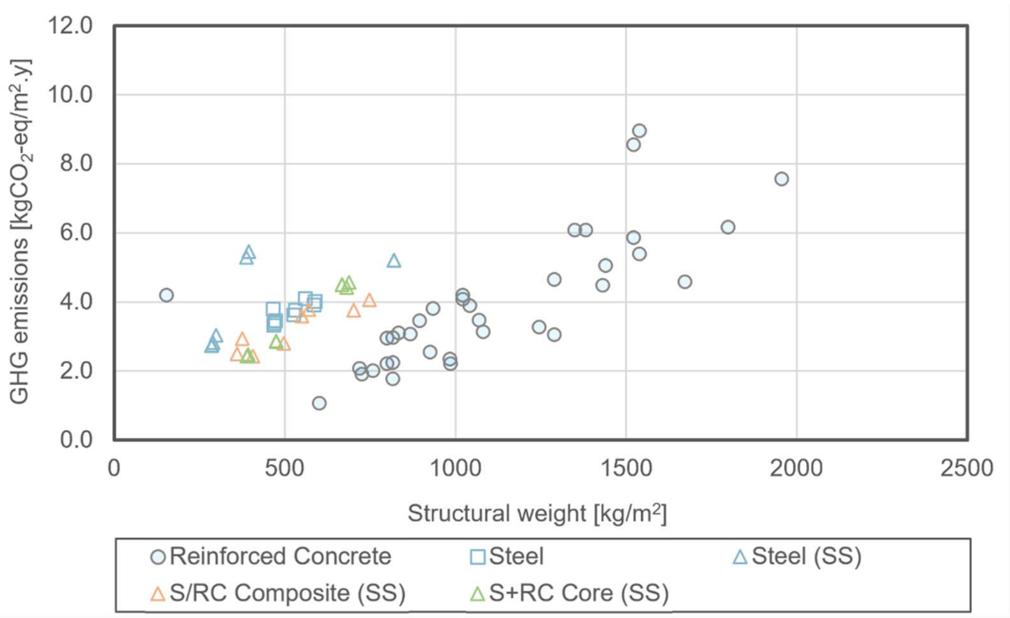

Figure A-4. Scatter plot of reinforced concrete buildings' embodied GHG emissions as a function of the structural weight by type of structural system.

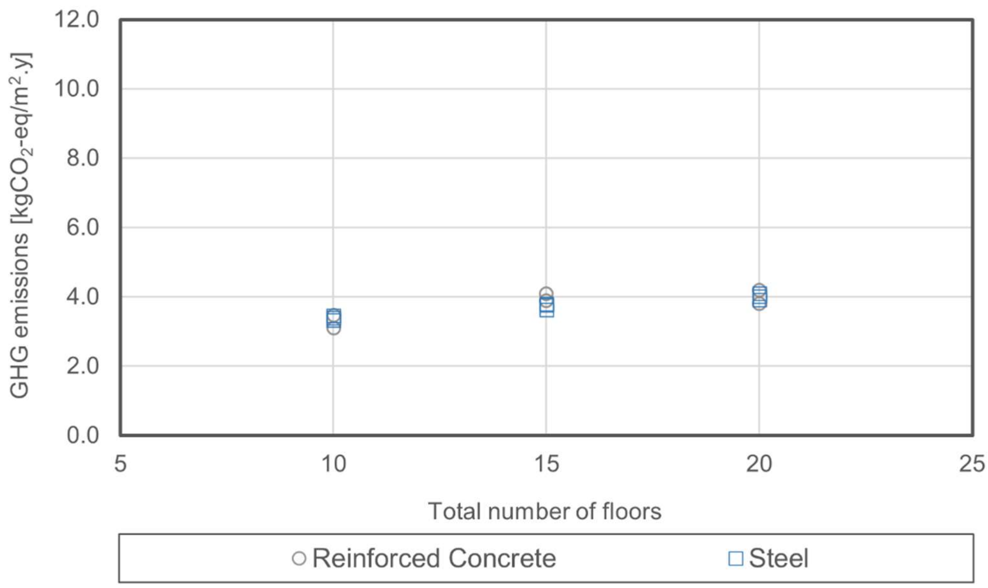

Figure A-5. Scatter plot comparing the embodied GHG emissions relative to the total number of floors between reinforced concrete structures and steel structures. Data extracted from Nadoushani and Akbarnezhad (2015a; 2015b).

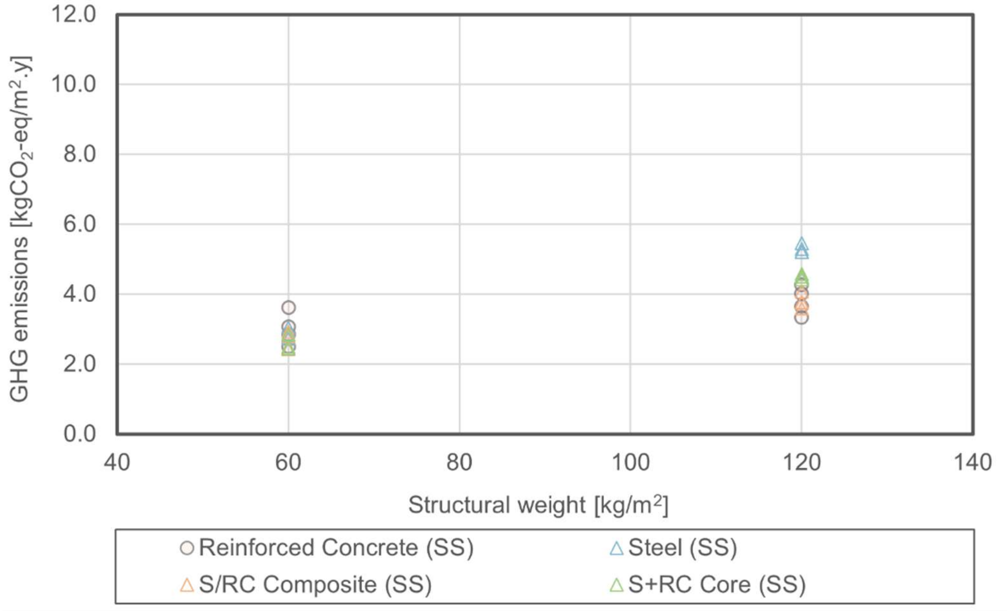

Figure A-6. Scatter plot comparing the embodied GHG emissions relative to the total number of floors between reinforced concrete, steel-concrete composite, and steel superstructures. Data extracted from Trabucco *et al.* (2016).

A.2.3 **Distribution fitting**

```r
library(MASS)
library(survival)
library(fitdistrplus)

set.seed(12)
#Import data and plot
my_data <- read.csv(file.choose())
plot(my_data$emissions, pch=20)

#Plot histogram of data
plotdist(my_data$emissions, breaks = 20,  histo = TRUE, demp = FALSE)

#Identify possible distributions
descdist(my_data$emissions, discrete = FALSE, boot = 500)

#Distribution fitting
dists <- c("gamma","lnorm","weibull")
fit <- list()
for (i in 1:length(dists))
  fit[[i]] <- fitdist(my_data$emissions, dists[i])

for (i in 1:length(dists))
  print(summary(fit[[i]]))

#Visual assessment
#Produce graphs of the PDF's, CDF's, Q-Q plots and P-P plots
par(mfrow = c(2,2))
plot.legend <- c("gamma","log-normal", "weibull")
denscomp(fit, legendtext = plot.legend,
         xlab = expression("GHG emissions [kgCO"[2]*"-eq/m"^2*".y]"),
         fitlty = c("dashed", "dashed", "dashed"),
         fitcol= c("#ef392c","#00a2ff", "#70be44"))
cdfcomp (fit, legendtext = plot.legend,
         xlab = expression("GHG emissions [kgCO"[2]*"-eq/m"^2*".y]"),
         fitlty = c("dashed", "dashed", "dashed"),
         fitcol = c("#ef392c","#00a2ff", "#0DB005"))
qqcomp  (fit, legendtext = plot.legend,
         fitcol = c("#ef392c","#00a2ff", "#70be44"))
ppcomp  (fit, legendtext = plot.legend,
         fitcol = c("#ef392c","#00a2ff", "#70be44"))

#Statistical assessment - Goodness of fit
f <- gofstat(fit, fitnames = c("gamma","log-normal","weibull"))
f
```

Figure A-7. Source code of the distribution fitting program written in R programming language.

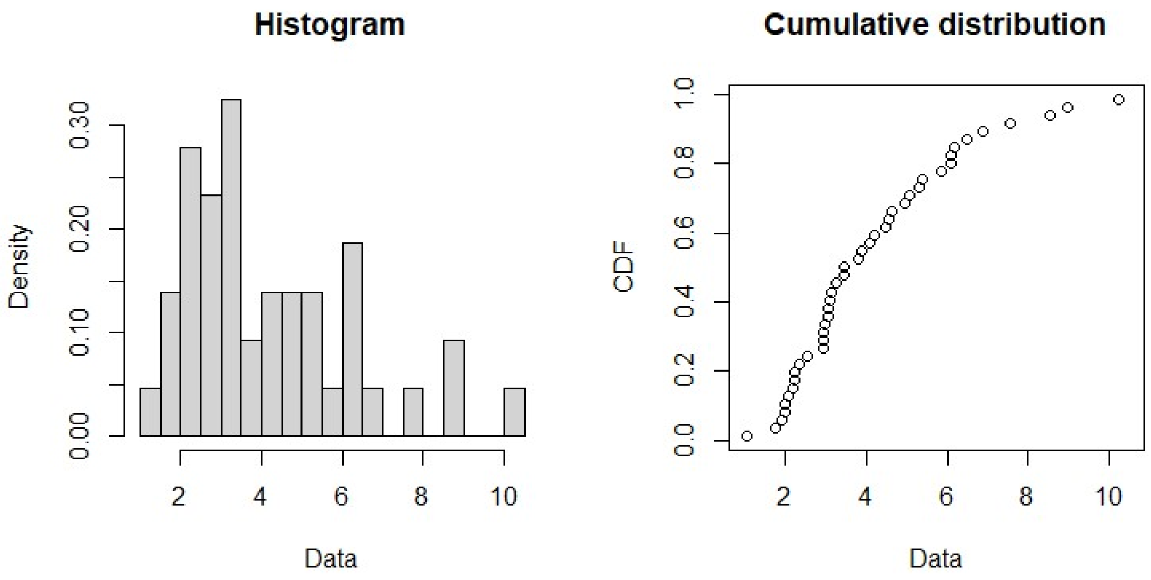

Figure A-8. Empirical histogram and cumulative distribution of the reinforced concrete sample.

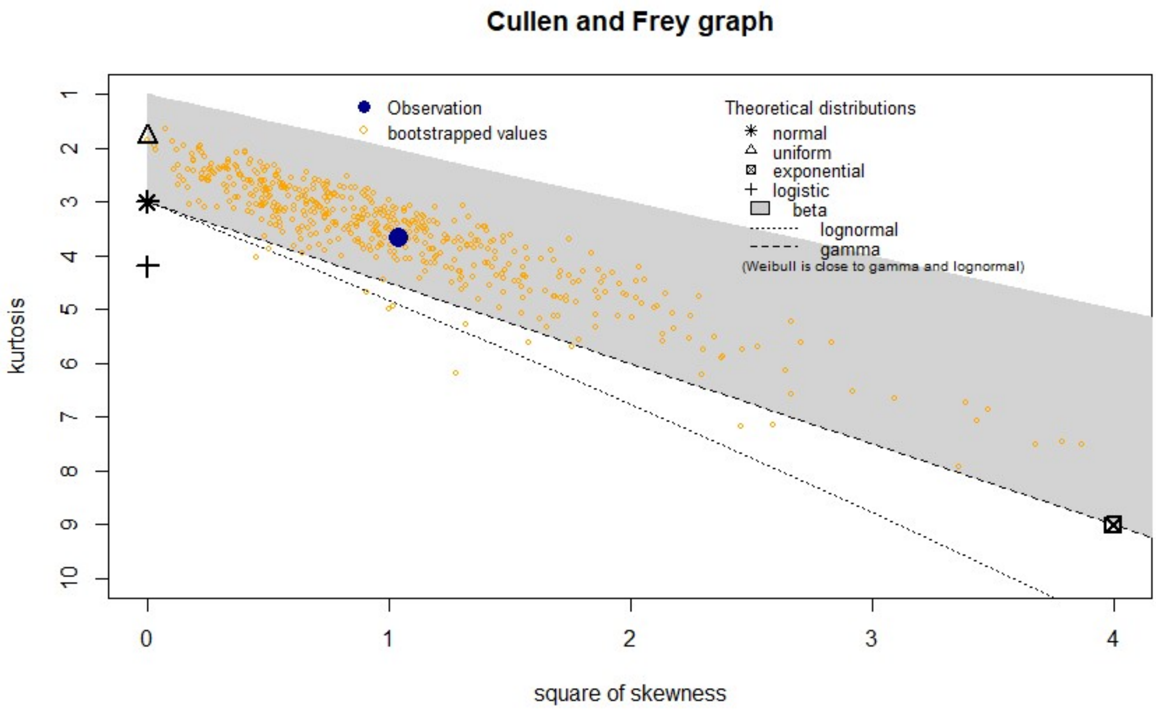

Figure A-9. Skewness-kurtosis plots (or Cullen and Frey graphs) of the reinforced concrete sample.

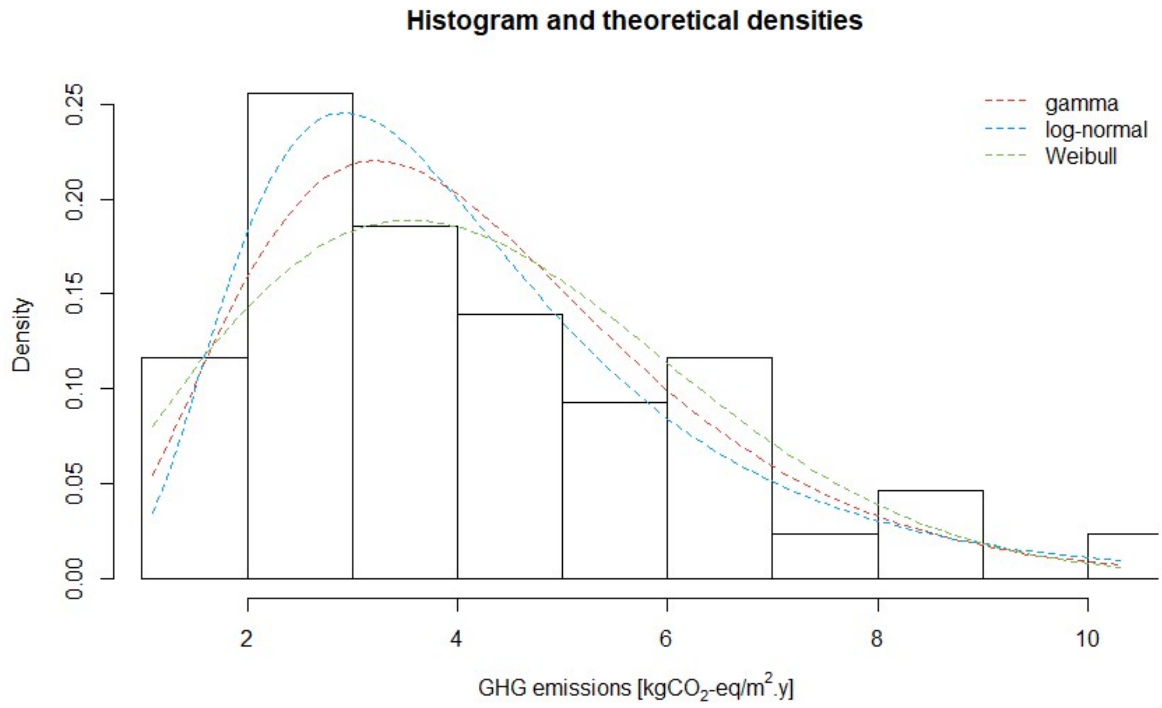

Figure A-10. Theoretical distributions' PDFs and empirical histogram of the reinforced concrete sample. Note that the empirical histogram here shown is slightly different from the one displayed in Figure A-8 because the number of bins is different.

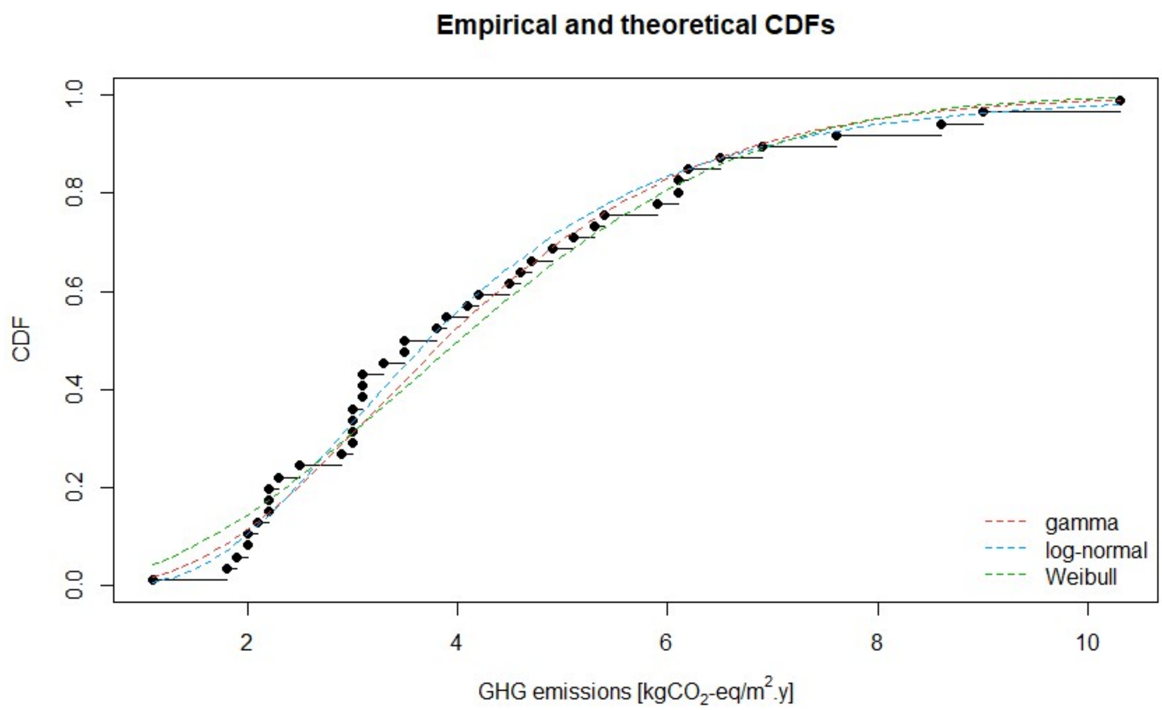

Figure A-11. Theoretical distributions CDFs and empirical CDF of the reinforced concrete sample.

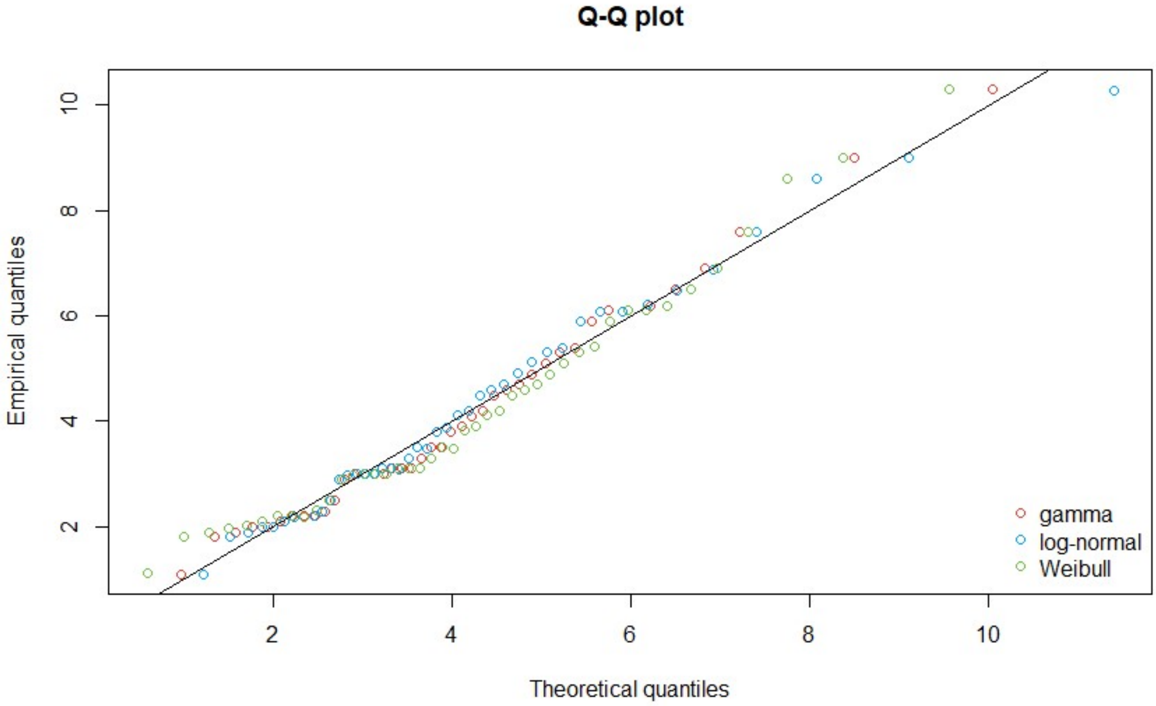

Figure A-12. Quantile-quantile plot from the reinforced concrete distribution fitting.

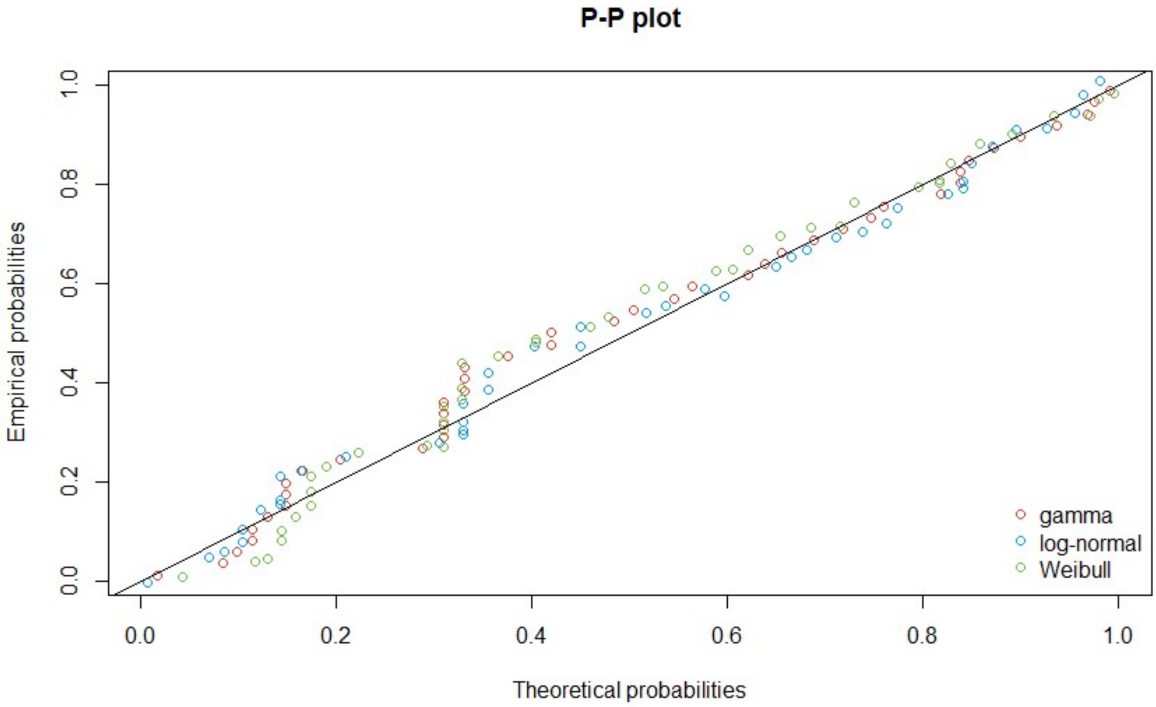

Figure A-13. Probability-probability plot from the reinforced concrete distribution fitting.

```
Goodness-of-fit statistics
                                  gamma log-normal   weibull
Kolmogorov-Smirnov statistic 0.11059397 0.08711682 0.1133906
Cramer-von Mises statistic   0.06278658 0.04172447 0.0937161
Anderson-Darling statistic   0.38509107 0.26879491 0.6098012

Goodness-of-fit criteria
                                  gamma log-normal  weibull
Akaike's Information Criterion 179.2850   178.2202 182.8049
Bayesian Information Criterion 182.8074   181.7426 186.3273
```

Figure A-14. Goodness-of-fit statistics and criteria from the reinforced concrete distribution fitting.

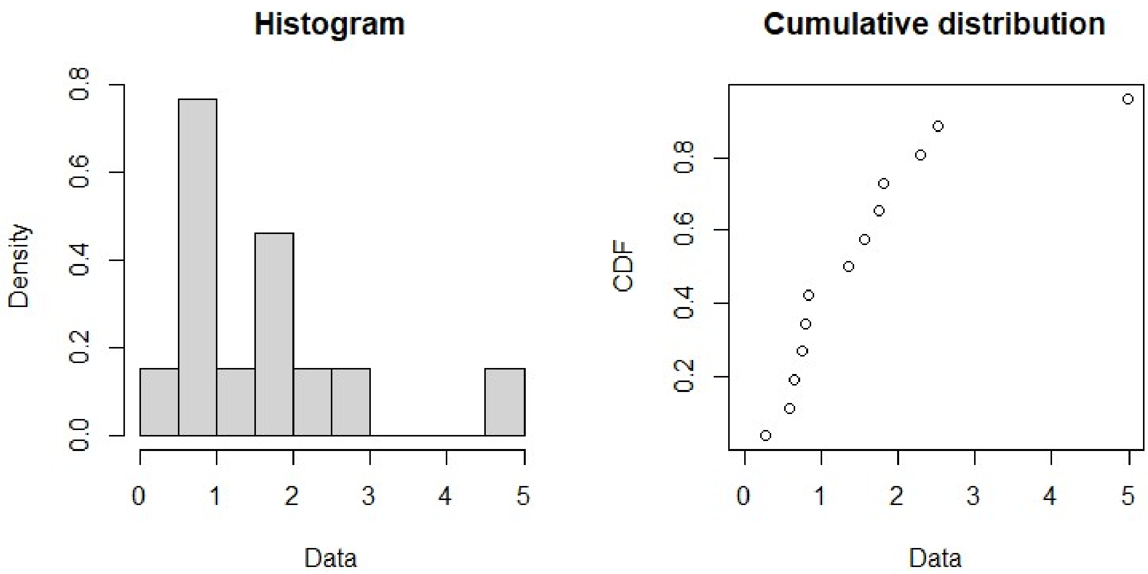

Figure A-15. Empirical histogram and cumulative distribution of the timber sample.

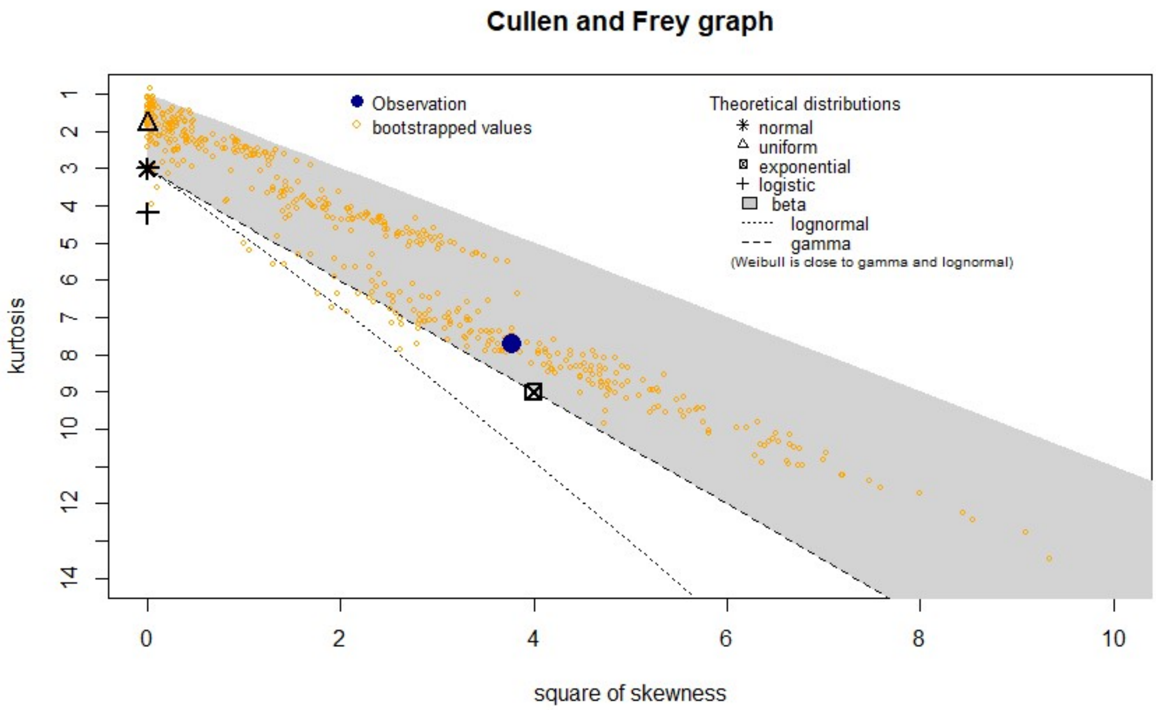

Figure A-16. Skewness-kurtosis plots (or Cullen and Frey graphs) of the timber sample.

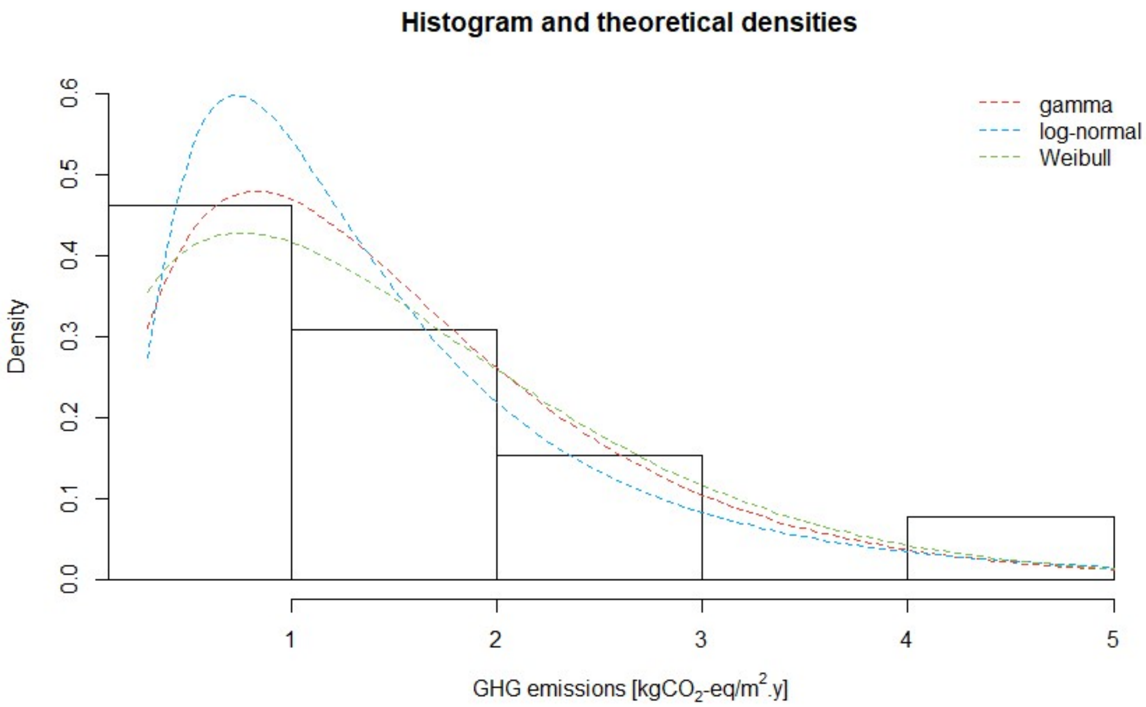

Figure A-17. Theoretical distributions' PDFs and empirical histogram of the timber sample. Note that the centre of the histogram appears to be next to zero because the number of bins here is lower than what was shown in Figure A-15.

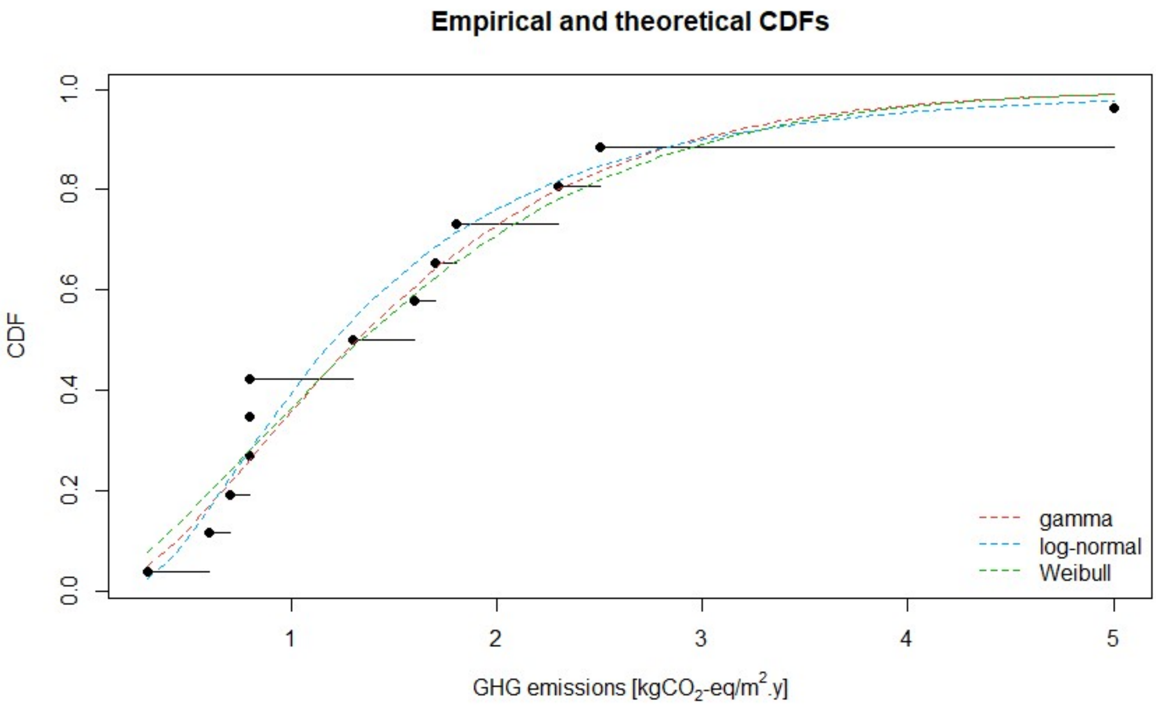

Figure A-18. Theoretical distributions CDFs and empirical CDF of the timber sample.

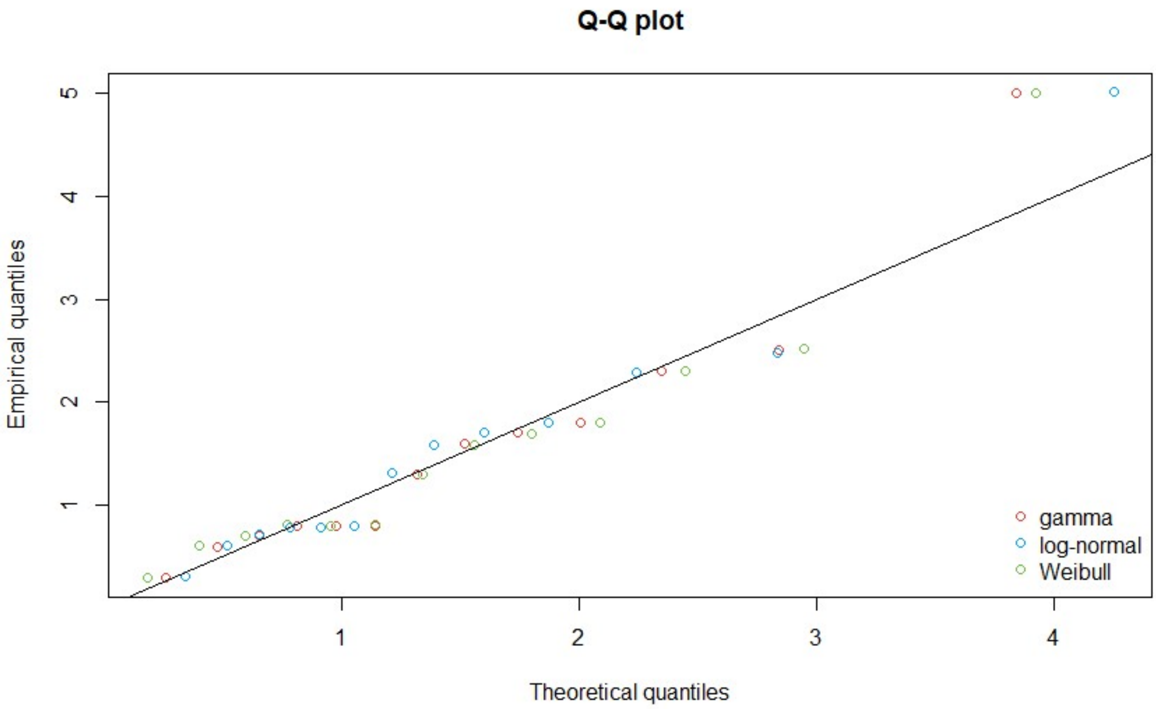

Figure A-19. Quantile-quantile plot from the timber distribution fitting.

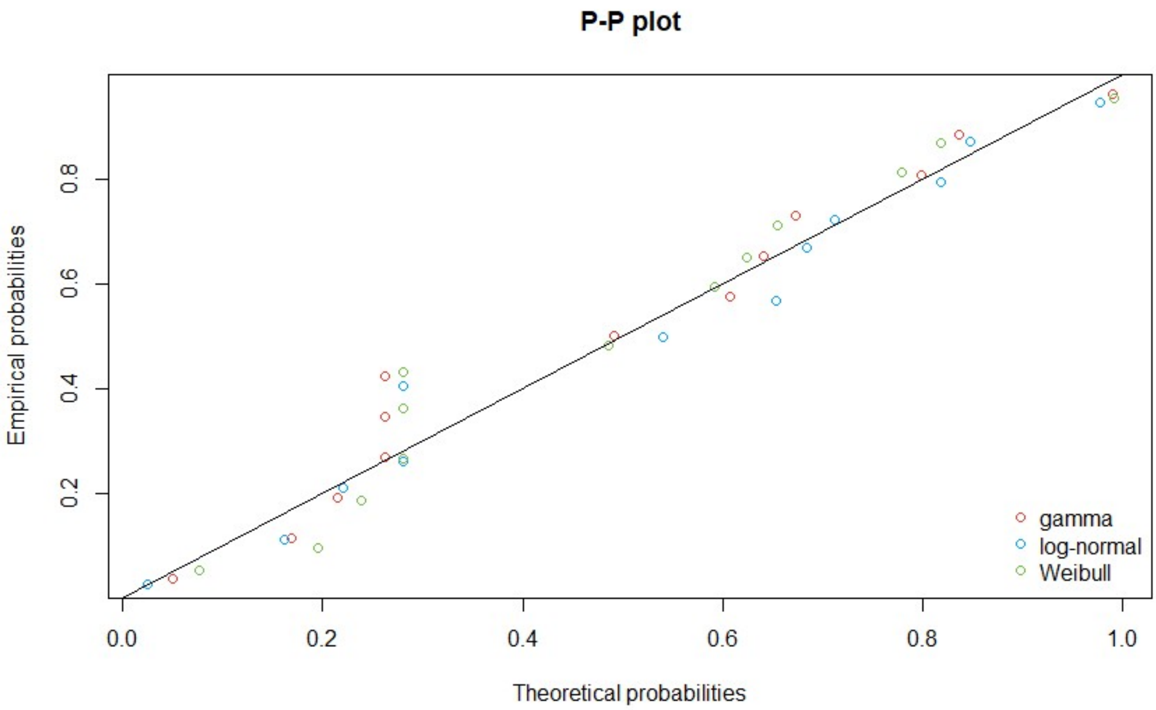

Figure A-20. Probability-probability plot from the timber distribution fitting.

```
Goodness-of-fit statistics
                                 gamma log-normal    weibull
Kolmogorov-Smirnov statistic 0.19911918 0.18108302 0.18079560
Cramer-von Mises statistic   0.05052266 0.04488634 0.05439109
Anderson-Darling statistic   0.33303162 0.26444855 0.37948492

Goodness-of-fit criteria
                                 gamma log-normal  weibull
Akaike's Information Criterion 37.90156   36.93553 38.79715
Bayesian Information Criterion 39.03146   38.06543 39.92705
```

Figure A-21. Goodness-of-fit statistics and criteria from the timber distribution fitting.

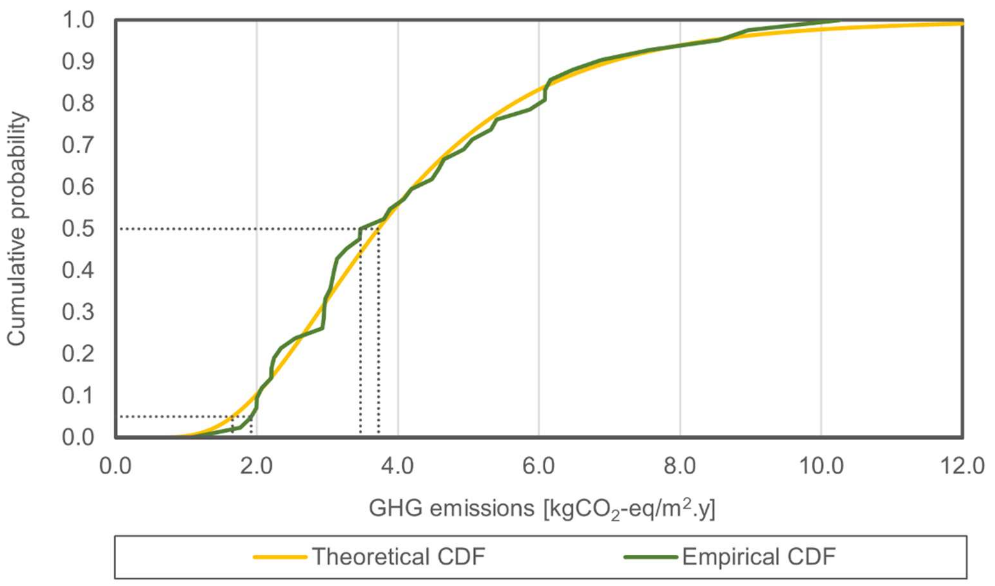

Figure A-22. Visual difference between the empirical and theoretical percentiles (5th and 50th) of reinforced concrete buildings.

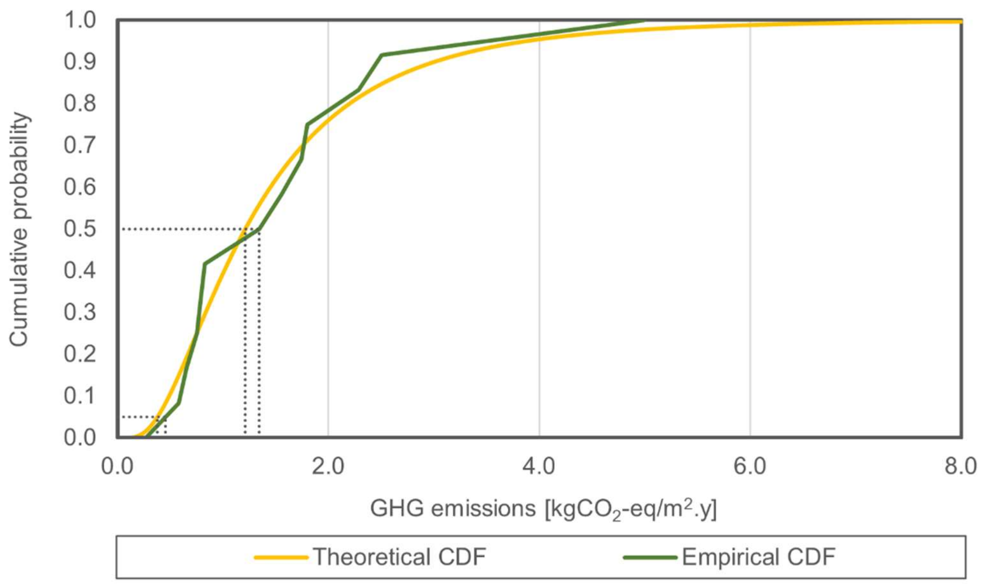

Figure A-23. Visual difference between the empirical and theoretical percentiles (5th and 50th) of timber buildings.

Appendix B

Data

This appendix presents the data that was used to assess the influence of the different factors on the embodied GHG emissions, perform the benchmark comparison and define the reference and target values for reinforced concrete and timber mid and high-rise structures.

Table A-3
Data of the cases collected from literature.

Study	Structural material	Total number of floors	LCA approach	Embodied GHG emissions A1-A3 ($kgCO_2$-eq/m².y)	Structural weight (kg/m^2)	Relative quantity of steel	Geographic region	Type of use
Reinforced concrete (RC)								
Biswas (2014)	RC	4	PB	4.5	1432	9%	Oceania	Office
Kofoworola and Gheewala (2008)	RC	39	IO	6.9	-	7%	Asia	Office
Kua and Wong (2012)	RC	6	PB	4.2	153	23%	Asia	Retail
Zhang and Wang (2017)	RC	17	PB	6.1	1382	4%	Asia	Residential
Wallhagen *et al*. (2011)	RC	4	PB	1.9	725	-	Europe	Office
Birgisdóttir *et al.* (2016)	RC	15	PB	6.2	1798	4%	Asia	Residential
Birgisdóttir *et al.* (2016)	RC	7	PB	2.1	719	-	Europe	Residential
Birgisdóttir *et al.* (2016)	RC	7	PB	2.0	758	-	Europe	Residential
Dokka *et al.* (2013)	RC	5	PB	3.1	867	4%	Europe	Office
Schlanbusch *et al*. (2017)	RC	5	PB	2.0	-	-	Europe	Educational
Birgisdóttir *et al.* (2016)	RC	6	PB	3.1	1081	-	Europe	Office
Birgisdóttir *et al.* (2016)	RC	9	IO	10.3	-	6%	Asia	Office
Birgisdóttir *et al.* (2016)	RC	8	PB	6.5	-	-	Europe	Residential
Ruuska and Häkkinen (2015)	RC	7	PB	4.9	-	-	Europe	Residential
Ruuska and Häkkinen (2015)	RC	7	PB	5.3	-	-	Europe	Residential
Robertson (2011)	RC	5	PB	7.6	1956	-	North America	Office
Dimoudi and Tompa (2008)	RC	7	PB	2.3	983	4%	Europe	Office
Yan *et al.* (2010)	RC	30	PB	5.9	1521	9%	Asia	Mixed-use
Yan *et al.* (2010)	RC	30	PB	8.6	1521	9%	Asia	Mixed-use
Nadoushani and Akbarnezhad (2015a)	RC	10	PB	3.5	895	6%	North America	N/A
Nadoushani and Akbarnezhad (2015a)	RC	10	PB	3.1	834	5%	North America	N/A
Nadoushani and Akbarnezhad (2015a)	RC	15	PB	4.1	1021	6%	North America	N/A
Nadoushani and Akbarnezhad (2015a)	RC	15	PB	3.9	1042	5%	North America	N/A

Study	Structural material	Total number of floors	LCA approach	Embodied GHG emissions A1-A3 ($kgCO_2$-eq/m².y)	Structural weight (kg/m^2)	Relative quantity of steel	Geographic region	Type of use
Reinforced concrete (RC)								
Nadoushani and Akbarnezhad (2015b)	RC	20	PB	4.2	1021	7%	North America	N/A
Nadoushani and Akbarnezhad (2015b)	RC	20	PB	3.8	935	7%	North America	N/A
John *et al*. (2009)	RC	6	PB	4.7	1289	3%	Oceania	Office
Skullestad *et al*. (2016)	RC	7	PB	2.2	817	2%	North America	Residential
Skullestad *et al*. (2016)	RC	7	PB	3.0	817	2%	North America	Residential
Skullestad *et al*. (2016)	RC	12	PB	2.2	800	2%	North America	Residential
Skullestad *et al*. (2016)	RC	12	PB	3.0	800	2%	North America	Residential
Skullestad *et al*. (2016)	RC	22	PB	5.4	1539	5%	Europe	Hotel
Skullestad *et al*. (2016)	RC	22	PB	9.0	1539	5%	Europe	Hotel
Eliassen (2019)	RC	6	PB	5.1	1440	4%	Europe	Residential
Eliassen (2019)	RC	9	PB	4.6	1672	4%	Europe	Residential
Peñaloza *et al*. (2013)	RC	4	PB	2.5	926	2%	Europe	Residential
Cattarinussi *et al*. (2016)	RC	19	PB	3.5	1070	5%	Europe	Office
Sandanayake *et al*. (2018)	RC	17	PB	6.1	1348	3%	Oceania	Retail
Lundgren (2014)	RC	9	PB	1.1	601	6%	Europe	Residential
Junnila (2004)	RC	9	PB	1.8	816	-	Europe	Office
Junnila (2004)	RC	5	PB	2.2	985	-	Europe	Office
Mao *et al*. (2013)	RC	27	PB	3.0	1289	4%	Asia	Residential
Mao *et al*. (2013)	RC	27	PB	3.3	1245	5%	Asia	Residential
Hofmeister *et al*. (2015)	RC	5	PB	2.9	-	-	Europe	Office
Ylmén *et al*. (2019)	RC	9	PB	3.0	-	3%	Europe	Office

Study	Structural material	Total number of floors	LCA approach	Embodied GHG emissions A1-A3 ($kgCO_2$-eq/m².y)	Structural weight (kg/m²)	Relative quantity of steel	Geographic region	Type of use
Timber (T)								
Birgisdóttir *et al*. (2016)	T (N/A)	7	PB	0.3	-	-	Europe	Residential
Ruuska and Häkkinen (2015)	T (Light-frame)	7	PB	2.5	-	-	Europe	Residential
John *et al*. (2009)	T (LVL + Timber-concrete slabs)	6	PB	1.8	426	-	Oceania	Office
Skullestad *et al*. (2016)	T (Glulam + CLT)	7	PB	0.8	191	-	North America	Residential
Skullestad *et al*. (2016)	T (Glulam + CLT)	12	PB	0.8	196	-	North America	Residential
Skullestad *et al*. (2016)	T (Glulam + CLT)	22	PB	1.3	347	-	Europe	Hotel
Eliassen (2019)	T (Glulam + CLT)	9	PB	2.3	833	-	Europe	Residential
Peñaloza *et al*. (2013)	T (CLT)	4	PB	0.8	189	-	Europe	Residential
Peñaloza *et al*. (2013)	T (CLT)	4	PB	0.6	132	-	Europe	Residential
Cattarinussi *et al*. (2016)	T (Post-tensioned Glulam)	19	PB	1.7	446	-	Europe	Office
Sandanayake *et al*. (2018)	T (CLT)	13	PB	5.0	1195	-	Europe	Mixed-use
Lundgren (2014)	T (Glulam + CLT)	9	PB	0.7	189	-	Europe	Residential
Hofmeister *et al*. (2015)	T (Glulam)	5	PB	1.6	-	-	Europe	Office
Timber (w/ CO_2 sequestration)								
Birgisdóttir *et al*. (2016)	T (Glulam + Timber-concrete slabs)	8	PB	0.8	912	-	Europe	Office
Birgisdóttir *et al*. (2016)	T (CLT)	8	PB	1.2	-	-	Europe	Residential
Robertson (2011)	T (Glulam + CLT)	5	PB	1.7	1359	-	North America	Office
John *et al*. (2009)	T (LVL + Timber-concrete slabs)	6	PB	-1.7	426	-	Oceania	Office
Vidal *et al*. (2019)	T (CLT)	4	PB	-0.1	622	-	Europe	Residential