Title: **Reducing the Carbon Emissions of High-Rise Structures from the Very Beginning**

Authors: Roland Bechmann, Managing Director, Werner Sobek AG
Stefanie Weidner, Project Leader, Sustainability, Werner Sobek AG

Subjects: Building Materials/Products
Construction

Keywords: Concrete
Timber

Publication Date: 2021

Original Publication: CTBUH Journal 2011 Issue IV

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Reducing the Carbon Emissions of High-Rise Structures from the Very Beginning

Roland Bechmann

Stefanie Weidner

Authors

Roland Bechmann, Managing Director
Stefanie Weidner, Project Leader, Sustainability
Werner Sobek AG
Albstrasse 14
Stuttgart 70597
Germany
t: +49 711 767 500
e: frank.heinlein@wernersobek.com
www.wernersobek.de/en/

Roland Bechmann is managing director and partner of the international engineering consultancy Werner Sobek. Having accomplished his diploma in Structural Engineering, Roland started working at Werner Sobek and soon rose to be appointed first principal, then general manager, and finally managing director and partner. Roland heads the department of competitions and is a specialist of project management, lightweight structures and steel constructions. He has extensive experience in various important high-rise projects, and since 2013, he has also been Country Representative of the Council on Tall Buildings and Urban Habitat (CTBUH).

Stefanie Weidner studied architecture at the University of Stuttgart, Germany, and the University of Melbourne, Australia. After her diploma she worked as a research assistant at the Institute for Lightweight Structures and Conceptual Design (ILEK), where she defended her doctoral thesis on resource consumption in urban structures in 2020. Since 2019, she works at Werner Sobek as an architect and project leader for sustainability, with an emphasis on embodied emissions and resource consumption. As of 2022, she will be head of Werner Sobek's new office in Copenhagen.

Abstract

Minimizing carbon emissions and reducing resource consumption in commercial high-rise buildings is an essential component of the building industry reducing its overall footprint. A concise study of design options with three levels of carbon emission production was undertaken for a real project proposed for a site in central Hamburg. The study showed that carbon emission reductions of up to 78 percent could be made by electing to design in hybrid timber as opposed to conventional concrete, and that a 47 percent reduction could be achieved through a concrete-optimization process.

Keywords: Concrete, Decarbonization, Hybrid Timber

Introduction

Until recently, carbon dioxide (CO_2) emissions of the building sector were mainly discussed with regard to the operating phase only. However, when considering a typical office building with high energy performance standards, less than half of the building's emissions are generated by the actual usage (Röck et al. 2020). More than 50 percent of all emissions linked to an individual building are embodied emissions. Some 64 percent of these embodied emissions result from the production and transport of the building materials, as well as from the erection of the building itself (Life Cycle Stage A). Twenty-two percent of embodied emissions are due to maintenance (Life Cycle Stage B), whereas 14 percent result from demolition and disposal (Life Cycle Stage C) (Röck et al. 2020).

What this also means: A third of the overall carbon emissions of a high-quality office building are emitted before the first occupant moves in. It takes over 50 years of annual operative emissions to reach the level of embodied emissions (Bechmann, Mrzigod & Weidner 2020).

Moreover, the climate-damaging impact of the initial embodied carbon is even greater than is suggested by this ratio. This is because an increasing decarbonization of the energy mix must be expected, provided that the objectives of the Paris Agreement are met: all energy generation worldwide must be fossil fuel-free by 2050 at the latest. Regarding the damage caused by emissions with relation to a particular date such as the year 2080, it is not only the amount of emissions that needs to be considered, but also the timing of their release. Greenhouse gases (GHGs) that are emitted when the building is constructed cause climate-relevant damage to the atmosphere right from the beginning. Operating emissions and the related damage, on the other hand, are very low to begin with, and only add up over time (Sobek 2022, Weidner et al. 2021).

Thus, it becomes obvious that future-proof sustainable design must focus much more on the materials we use for construction and on our methods of construction. This paper will discuss methods of minimizing carbon emissions and reducing resource consumption in commercial high-rise buildings, through the example of comparing the global warming potential (GWP) of three designs, as considered for a tower in Hamburg, Germany.

Carbon Optimization for a Commercial High-Rise

For a client in Hamburg, the authors' firm investigated in detail the potential minimization of carbon emissions that can be achieved for a new tower, to be built in a much-coveted central location. In this particular case, minimizing the embodied carbon was not only a desire of the client, but it also helped the client to purchase the plot for the tower in the first place. In the German market, there is an increasing call for cities not to sell their real estate plots to the highest bidder, but rather to the most sustainable concept (Gefroi 2008). Sustainable criteria thus become just as important a factor as the selling price in the bidding matrix.

In this study, the authors investigated three different designs and performed a life-cycle analysis (LCA) for each of these designs (see Figure 1). The primary focus of the study centered on emissions embedded in the load-bearing structure of the building, which arise during the construction in life cycle stages A1–A3 (see Figure 2). For the data collection, a generic German database was used (DIN 2013). Based on this study, the client and the land purchaser decided which design to pursue. The three designs considered were:

a. Typical concrete building as a benchmark design
b. Optimized concrete tower
c. Hybrid concrete-timber tower

All three design typologies were to rise 29 stories above ground and have three stories below ground. A gross floor area (GFA) of 45,000 square meters was set as the comparative value.

Design A: Benchmark Tower

In line with most tall commercial buildings in Germany, the first design consists of flat concrete slabs and cores. Flat slabs allow for an easy integration of technical building equipment and a low floor-to-floor-height.

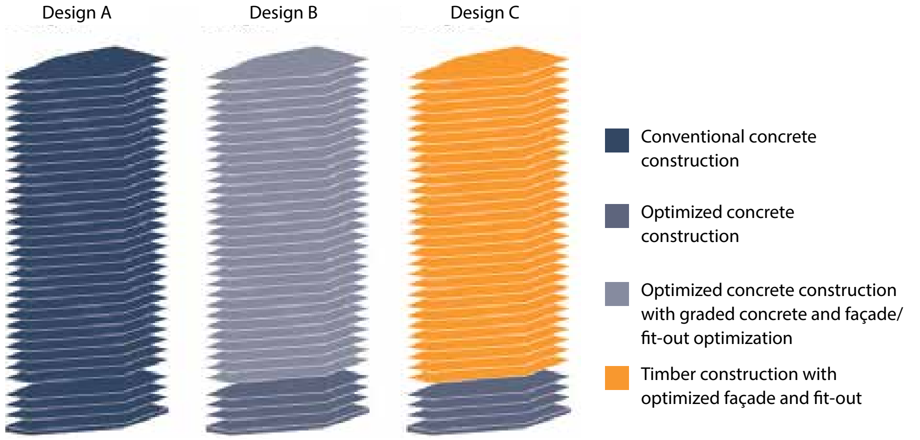

Figure 1. Systematic illustration of the three design cases for a tower in central Hamburg.

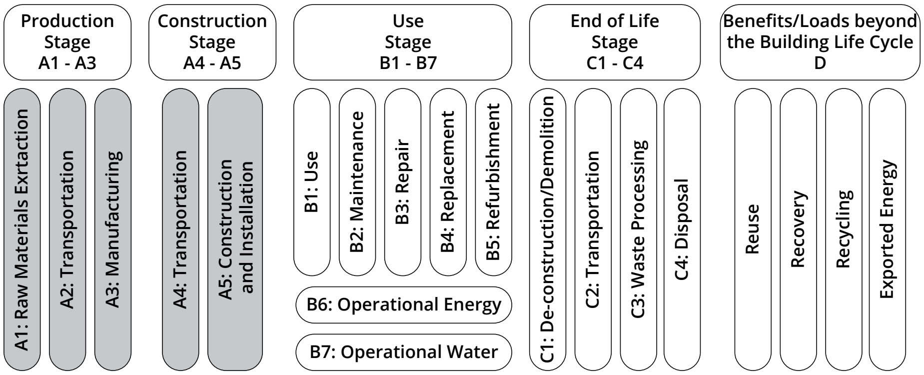

Figure 2. The system boundaries of an LCA analysis. The specific stages taken into consideration in this study are marked in grey. Source: EN 15978:2011, redrawn by CTBUH

> "A third of the overall carbon emissions of a high-quality office building are emitted before the first occupant moves in."

Moreover, owing to the low labor costs for installing the reinforcing elements and formwork and their simple creation on-site, reinforced flat concrete slabs have emerged as a standard in Germany and many other countries—despite the fact that this is not a material-optimized system (Berger, Prasser & Reinke 2013).

The façade consists of a typical unitized system. The building fit-out with raised floors and plaster walls was also assumed as typical.

The structural components of a conventionally-built benchmark tower amount to a total of 13,834 metric tons of carbon dioxide equivalent (t CO$_2$-eq.). Per square meter of GFA, this would result in 307.4 kg CO$_2$-eq. On average, it shows that concrete is responsible for two-thirds of all

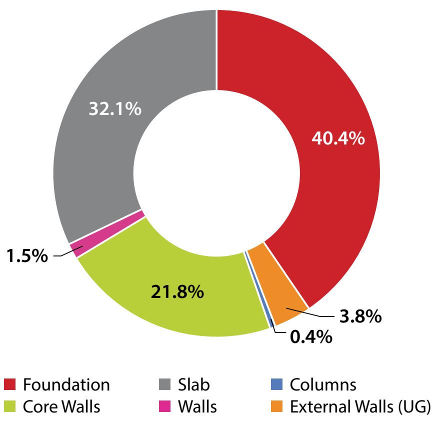

Figure 3. Global warming potential (GWP) for life cycle phases A1–A3 of the structural components of the base-case concrete building (Design A).

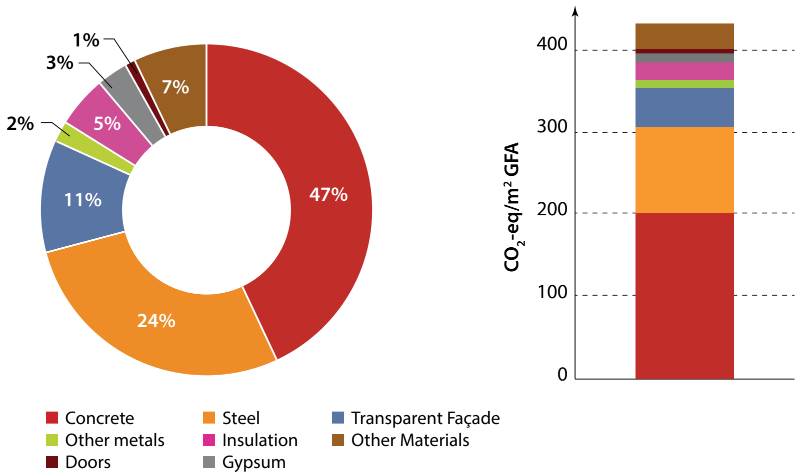

Figure 4. Distribution of embodied carbon throughout the base-case concrete building (Design A), excluding MEP and tenant fit-out.

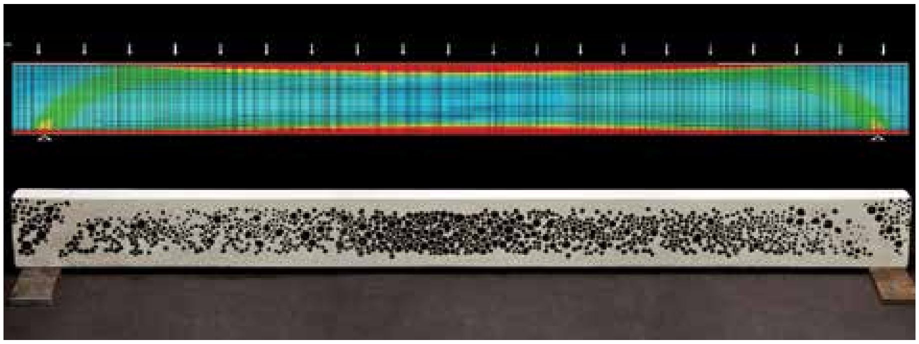

Figure 5. The graded-concrete concept incorporates cavities in beams and floors where there is the lowest potential implication for structural strength. Doing this reduces the amount of concrete and rebar required, and thus the emissions of the project, by 12 percent. © ILEK

embodied emissions resulting from the structure, and reinforcing steel accounts for one-third. Figure 3 shows the distribution of the GHG emissions among the structural components.

Including façade and primary fit-out (tenant-specific fit-out and MEP systems not included) the authors determined a total sum of 19,484 t CO_2-eq. or 433 kg CO_2-eq./m^2 GFA. The distribution of embodied carbon emissions throughout the entire building is shown in Figure 4.

Design B: Optimized Concrete Design

The idea of this design approach was to minimize the carbon footprint of the tower as much as possible while still using concrete, acknowledging that concrete will remain a major construction material in the foreseeable future, especially for high-rise buildings. The optimizations included a specific concrete mix as well as specifically-adjusted structural systems and material manufacturing, thus combining carbon-optimized design and circular design approaches.

Specifically, the following optimizations were investigated:

Slab Design

Since all design approaches with supporting beams beneath floor slabs lead to increased floor-to-floor height and more complex MEP pipe routing, it was decided to stick to the outer shape of a flat slab. Instead of optimizing the outer geometry, the so called "graded concrete" concept developed by Prof. Werner Sobek (2016) was applied (see Figure 5). For a graded concrete slab, cavities are incorporated in areas of the slab that are not fully utilized from a structural point of view. Typically, hollow plastic elements are used for similar purposes. However, graded concrete goes one step further, as it allows for unpolluted concrete ceilings and a much finer distribution of cavities—this results in better recyclability and a higher adjustability of floor heights (Schmeer & Sobek 2019). Furthermore, this technology allows for an increase of the cavity proportion by means of compression and can be applied on biaxially-stressed slabs as well.

By reducing not only the amount of embedded concrete, but also consecutively the amount of reinforcing steel, the overall weight of the floor slabs can be drastically reduced. Consequently, the dimensions of the foundation, walls, and columns can also be decreased, which leads to total savings of 2,319 t CO_2-eq. or 51.6 kg/m^2 GFA. Thus, a reduction of 12 percent of the whole building's A1–A3 emissions can be achieved just by optimizing the slab design.

Low-Carbon Concrete Mix

The decisive factor for the high CO_2 emissions associated with concrete is the burning process necessary for producing Portland cement clinker. In Germany, a mean total of around 600 kilograms of CO_2 is emitted by producing one metric ton of cement clinker (IBU 2017). When burning the clinker, limestone (which consists mostly of the chemical substance calcium carbonate, $CaCO_3$), is heated to up to 1,400 degrees Celsius. Calcium oxide (CaO)—the main component of cement—is the result of this process. However, as a by-product of the chemical reaction, there is also a huge amount of CO_2 emissions (representing 59 percent of all process-related emissions). Further CO_2 emissions are generated due to fossil fuels used to heat the rotary kiln (19 percent) and further energy supply in the form of electricity (12 percent).

An expedient optimization approach for the time being is to minimize the Portland cement clinker content in the concrete used. To a certain extent, this can be achieved by means of precise measurements, in which CO_2 consumption is taken into account, and to therefore allow for lower-strength concrete to be used wherever possible. In addition to this, part of the Portland cement clinker content can be replaced with other aggregates. Suitable substitutes include slag sand, a by-product of the steel industry, and fly ash, a byproduct of coal-fired electricity generation. However, high CO_2 emissions are released when producing these two substances, as well. In the LCA, these emissions are mostly allocated to the production of steel or electricity, rather than cement, as allocation is based on the product price. These substitutes are therefore not a long-term solution; however, it is certainly reasonable to use them in an interim phase to activate synergies.

For the optimization of the concrete mix used for this design, a CEM III cement with a high content of slag sand was used. The lower CO_2 emissions of this cement were verified through an environmental product declaration (EPD). Also, due to discussions and negotiations, a cement supplier for Hamburg agreed to cover 100 percent of the energy needs for this cement from fossil-free sources, based on renewable energies and on alternative fuels. This led to an additional 2.2 percent reduction of concrete-related CO_2 emissions in phases A1–A3.

In addition, it was assumed that about 50 percent of the gravel would be substituted by crushed demolition materials (i.e., recycled concrete). This also gives rise to slight benefits with regard to the CO_2 balance, thanks to shorter transport distances: demolition materials can usually be sourced in the immediate vicinity of the concrete factory, and do not need to be brought in from a gravel pit located further away. Thus, life cycle stage A2, which accounts for approximately 4 percent of A1–A3 emissions in concrete (IBU 2018), can be decreased by an average of 20 percent. Nonetheless, the main purpose for using recycled concrete is to reduce the extraction of materials from nature.

Reinforcing Steel

In typical commercial projects in Germany, steel is mostly used in reinforcement. Other than rolled sections, reinforcing steel is produced with up to 100 percent recycled scrap steel. Emissions from the primary steel production, which are widely discussed, therefore do not apply to the carbon balance. For reinforcing steel, the CO_2 emissions that must be taken into account evolve due to the energy sources used for melting the scrap metal on the one hand, and processing it (by creating bars or mats and transporting them to the construction site) on the other hand. In modern rolling mills, all these forming processes are electrified. Thus, it was possible to agree with the local reinforcement manufacturer only to use electricity generated by combustion-free energy sources. Furthermore, the transportation to the site was optimized, so that the carbon footprint of the reinforcement could be drastically reduced from 683 kg CO_2-eq/t in a generic dataset to around 250 kg CO_2-eq/t in this specific case.

Since in the benchmark tower, reinforcing steel is responsible for 24 percent of the total embodied emissions, minimizing these emissions led to an additional reduction of 15.4 percent, for a total of 8,136 t CO_2-eq. Thus 58 percent, or 252.2 kg CO_2-eq./m^2 GFA remains, when all three measures are applied.

Interior Fit-Out

The design also used a concept for the interior work, in order to achieve a maximum reduction of resource consumption and CO_2 emissions. This concept is based on the Urban Mining & Recycling (UMAR) Experimental Unit, part of the Next Evolution in Sustainable Building Technologies (NEST) research building on the campus of the Swiss Federal Laboratories for Materials Science and Technology (Empa) in Dübendorf, Switzerland (Heinlein 2019). The measures applied included clay support plates with clay plaster, which are used instead of interior walls made of plasterboard, and the use of products that are only temporarily leased from the manufacturer.

The carpet tiles, for example, will be returned to the manufacturer after use and processed for reuse. An interdisciplinary planning process guarantees that only fully separable connections are used for joining any fit-out materials, to allow for easier maintenance and fully recyclable dismantling. These measures also contribute to a limitation of embodied emissions from maintenance activities.

Thereby, replacing plasterboard and conventional carpets saves an additional 2 percent of the embodied emissions, or 10 kg CO_2-eq./m^2 GFA.

Façades

In the context of the study, a largely carbon-neutral façade was designed using recycled materials as well as biodegradable materials and wood. Untreated wooden support profiles made of silver fir are intended for the transparent section. These are covered with recycled aluminum from the outside, to provide for weather protection. Planning provides for insulating glass panes that also feature very high recycled content. The small opaque façade area of the building is constructed from recycled bricks, with hemp-based insulation material on the inside. By the means of these additional measures, the façade specific emissions can be further decreased by 12 kg CO_2-eq./m^2 GFA.

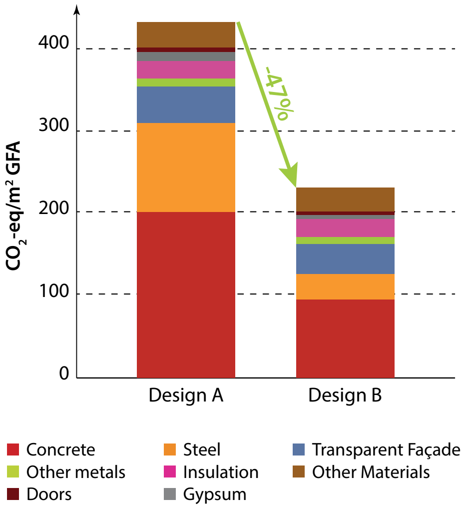

Figure 6. A reduction of 202 kg/m^2 of CO_2 equivalent, or 47 percent, was achieved by designing optimizations for a conventional concrete building (Design B).

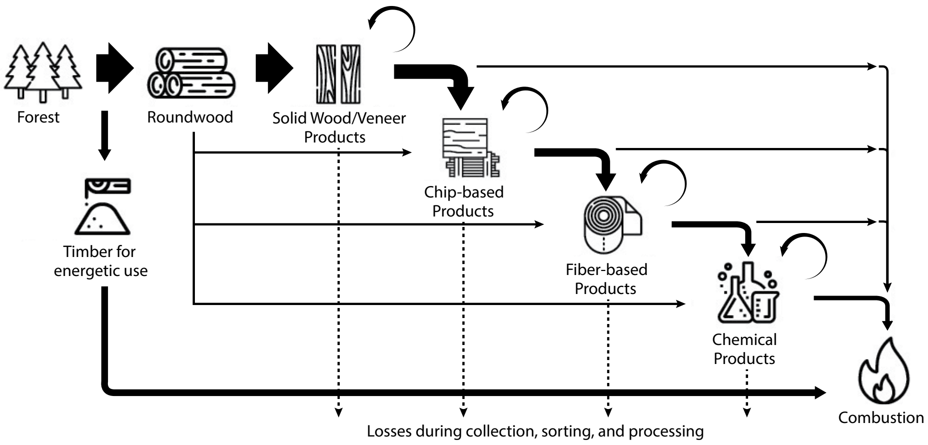

Figure 7. Timber cascade showing how the varying usability of timber products leads to a longer time of CO_2 sequestration, figure based on Umweltbundesamt 2020.

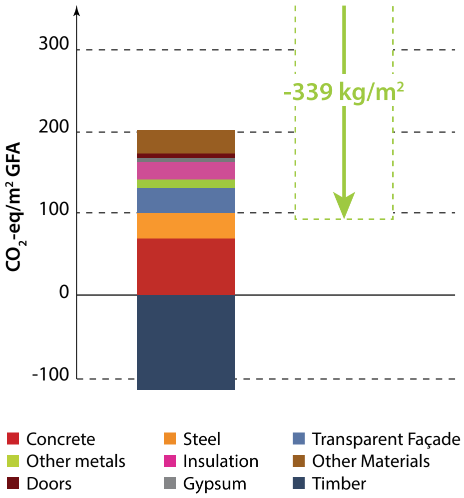

Figure 8. Use of a hybrid timber approach (Design C) represents a reduction of 339 kg/m^2 of CO_2 equivalent, or 78 percent reduction from the base design case.

Compared to a standard reference building, a total sum of 9,090 t CO_2-eq. was saved from being emitted into the atmosphere, resulting in a reduction of the embodied emissions by 47 percent. Figure 6 depicts the total reduction of an optimized concrete tower for life cycle stages A1–A3. In terms of completeness, it must be noted that opaque façade areas generally emit less carbon during production processes than transparent façades. Therefore, an even higher reduction could be reached by decreasing the amount of glazing.

The measures described above led to an additional reduction of embodied emissions by almost 50 percent. In other words, even when building in concrete, it is possible to cut the emissions of a high-rise tower in half. As concrete will remain one of the most relevant materials for construction, this seems a promising result.

Design C: Hybrid Timber Tower

As a third design option, the construction of the tower as a hybrid timber-concrete building was investigated. This solution assumed the foundation, the underground levels, and the stiffening core to be concrete, while the slabs of all upper floors were designed as 200-millimeter timber panels with 100-millimeter concrete topping slabs. All other measures already introduced for Design B were applied to this design as well.

In lieu of a full timber building, this hybrid is a solution commonly found in Germany, as it does not require special compensations for fire safety. The concrete layer on the slabs provides sufficient structural and acoustical damping, so that the technical quality is comparable to a full concrete building, while the timber provides additional aesthetic benefits. For structural reasons, steel beams support the timber floor slab. These steel profiles are produced via the electric-oven route, and therefore a relatively small 300 kg CO_2-eq./t are emitted during their production. Thus, per square meter of floor slab, 105.2 kg CO_2-eq. are sequestered during the A1–A3 stages.

Obviously, timber is suitable for minimizing the carbon footprint of a building. During the growth process, wood extracts CO_2 from the air and stores carbon. Slabs constructed as a wood panel design account for only about a fifth of the mass, and instead of a negative CO_2 footprint, they provide for a positive CO_2 storage effect. The emerging trend toward adapting mass timber for high-rise building projects is therefore to be welcomed. In a fully sustainable approach, the planting of a sufficient number of trees before the start of the construction activity would be necessary. It should also be noted that the emission-negative effect of timber slightly distorts the result when only stages A1–A3 are considered, since it leads to massive savings in the production phases, whereas stage C offsets these savings.

Alas, keeping wooden products equal in level in the timber cascade (see Figure 7), is still the exception today, since glues and coatings hinder the recycling process. Thus, in life cycle stage D, only the option of combustion exists. The carbon that has been sequestered many years before the tree became a construction material, is being emitted into the atmosphere at a state in global history when it is most unwanted. Therefore, the authors believe it is inappropriate to give sustainability credits for timber recycling that consumes high levels of energy.

However, the results for A1–A3 clearly outline the positive effect of the timber version (see Figure 8). The amount of wood embedded in the floor slabs sequesters 4,936 t CO_2. The whole building therefore only accounts for 22 percent of the embodied emissions, or 93.8 kg CO_2-eq./m^2 GFA, compared to the benchmark tower. Instead of 19,484 t CO_2, this building design emits only 4,219 t CO_2.

Table 1 summarizes the compiled data per m^2 GFA and Figure 9 gives a visual overview of the total reduction.

Conclusion

A significant reduction of carbon emissions is possible. Due to the relevance of minimizing carbon emissions, designers of high-rise projects will have to justify all future design decisions with regard to the specific climate repercussions thereof. Contrary to social sustainability effects or the uncertainties related to the dynamics of individual facility management, the embodied carbon footprint can be calculated quite precisely and thus evaluated objectively. Designers and developers must adapt their selection of materials accordingly. The example shown here, a comparison of a standard concrete tower to an optimized concrete and a hybrid timber tower, show the variety of solutions that can be used. To achieve this in budget-driven real estate projects, architects and engineers must understand the interdependencies of their choices, and in the future, work hand-in-glove. ■

Unless otherwise noted, all image credits in this paper are to Werner Sobek AG.

References

Bechmann, R., Mrzigod, A. & Weidner, S. (2020). "Embodied Emissions in the Built Environment." Stuttgart.

Berger, T., Prasser, P., Reinke, H. G. (2013). "Einsparung von Grauer Energie bei Hochhäusern." *Beton Stahlbetonbau* 108: 395–403. https://doi.org/10.1002/best.201300019.

Deutsches Institut für Normung e. V. (DIN) (ed.) 2013. *SN EN 15804+A1: 2013; Sustainability of Construction Works – Environmental Product Declarations – Core-Rules for the Product Category of Construction Products.* Berlin: DIN.

Gefroi, C. (2008). "Die Stadt als Kaufmann. Architekturqualität und Wirtschaftlichkeit in der Hafencity – Wid-erspruch oder Ergänzung?" Accessed 29 September 2021. https://www.db-bauzeitung.de/allgemein/architekturqualitaet-und-wirtschaftlichkeit-in-der-hafencity-widerspruch-oder-ergaenzung/.

Heinlein, F. (2019). *Recyclable by Werner Sobek.* Stuttgart: av edition GmbH.

Institut Bauen und Umwelt e. V. (IBU). (ed.) (2018). *Beton der Druckfestigkeitsklasse C 30/37.* Berlin: IBU.

Institut Bauen und Umwelt e. V. (IBU). (ed.) (2017). *Zement.* Berlin: IBU.

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T. & Passer, A. (2020). "Embodied GHG Emissions of Buildings – The Hidden Challenge for Effective Climate Change Mitigation." *Applied Energy* 258. https://doi.org/10.1016/j.apenergy.2019.114107

Schmeer, D. & Sobek, W. (2019). "Gradientenbeton." In *Beton Kalender 2019*, edited by Konrad Bergmeister, Frank Fingerloos & Johann-Dietrich Wörner, 455–76. Berlin: Ernst & Sohn. https://doi.org/10.1002/9783433609330.ch6

Sobek, W. (2016). "Über die Gestaltung der Bauteilinnenräume." *Fest-schrift Zu Ehren von Prof. Dr.-Ing. Dr.-Ing. E.h. Manfred Curbach*, edited by Silke Scheerer & Ulrich van Stipriaan, 62–76. Dresden: Institut für Massivbau der TU Dresden.

Sobek, W. (2022). *Non Nobis.* Stuttgart: av Edition.

Weidner, S., Mrzigod, A., Bechmann, R. & Sobek, W. (2021). "Graue Emissionen im Bauwesen – Bestands -aufnahme und Optimierungsstrategien." *Beton- und Stahlbetonbau.* https://doi.org/10.1002/best.202100065

All numbers in kg CO_2-eq./m^2 GFA		Design A	Design B	Design C
Reduction	Graded concrete slabs	-	-52 kg	-
	Low-carbon concrete mix	-	-74 kg	-57 kg
	Low-carbon reinforcing steel	-	-55 kg	-45 kg
	Optimizing interior fit-out façade	-	-21 kg	-21 kg
	Timber slabs	-	-	-110 kg
Embodied Emissions in kg CO_2-eq./m^{2}GFA		433 kg	202 kg	94 kg

Table 1. Table summarizing the carbon reductions undertaken for a base reference concrete building (Design A), and optimized concrete building (Design B), and a hybrid timber-concrete building (Design C).

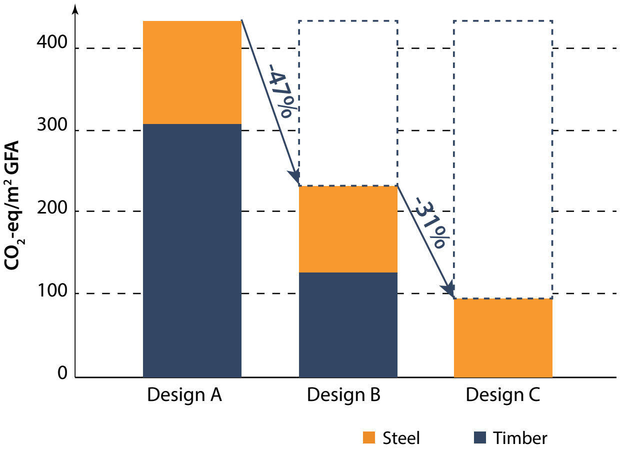

Figure 9. Overall reduction of embodied emissions, comparing each of the three design cases: standard concrete construction (Design A), optimized concrete construction (Design B), and hybrid timber (Design C).