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Embodied Carbon Benefits of Reusing Structural Components in the Built Environment: a Medium-rise Office Building Case Study

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ABSTRACT: This paper provides parametric estimates of embodied carbon reductions when structural components are reused in a typical office building. First, a lower bound of structural material quantities is estimated for a typical steel frame structure in a low-rise office building. The embodied carbon of this conventional design is then compared with values collected from a series of similar existing steel buildings (deQo database) as benchmark. Various scenarios regarding the impact of selective deconstruction, transportation, and cross-section oversizing are modelled and parameterized. The study eventually computes carbon savings over one life cycle of the building project. Results show that reuse remains beneficial for long transport and high oversizing. The discussion calls for more comprehensive studies and refined metrics for quantifying selective deconstruction.
KEYWORDS: Embodied carbon, Reuse, Circular Economy, Office Building, Steel

1. INTRODUCTION

1.1. Embodied carbon and waste

The Intergovernmental Panel on Climate Change recommends that the building sector becomes zero carbon by 2050 in order to meet the Paris Climate Agreement [1,2] and to avoid extreme climate catastrophes. The whole life greenhouse gas (GHG) emissions expressed in carbon dioxide equivalent (CO_2e) and shortened as “carbon” in this paper, include both, operational and embodied carbon of buildings.

- Operational carbon relates to GHG emissions during the use phase of the building, which includes heating, cooling, ventilation, lighting, and equipment.
- Embodied carbon refers to GHG emissions during all other life cycle phases: material extraction, component production, transport, construction, maintenance, and demolition.

Recent technical standards and political initiatives have successfully reduced the operational carbon of buildings. However, significant improvements are still required to lower the embodied carbon of new buildings.

Besides, up to 50 % of material use in Europe is related to the built environment [3, 4], which generally constitutes the most resource intensive sector in many industrialized countries [5]. In addition, more than 30 % of the waste generated in Europe originates from the construction sector [6-8]. From these observations, it follows that the design and construction of buildings and infrastructures could be improved by making a more efficient use of materials.

Load bearing systems, because of their high material mass and energy intensive production, are currently responsible for the biggest portion of embodied carbon emissions and waste production in buildings [9]. Structural engineers have therefore a responsibility to reduce the environmental impact of buildings.

1.2. Circular economy and reuse

A potential path to increased sustainability of building structures is the integration of circular economy principles in the structural design. Circular economy, a concept originally introduced by architect and economist Walter Stahel [10], advocates a closed loop flow of materials and components in order to extend their service life [11]. The European Commission considers that circular economy would boost competitiveness, innovation, local employment, business opportunities, and social integration and cohesion while protecting against shortage of resources, volatile prices, and air, soil and water pollution [12]. Circular economy involves five strategies: reduce, repair, reuse, recycle, and recover energy. Most sources, including the European Union [13], prioritize them in the same sequence, i.e. reduce must take precedence over repair, repair over reuse, reuse over recycling, and recycling over energy recovering. Although academic literature evolves to bring circular economy into the building sector, its application in building practice remains difficult due to a number of economic, cultural and technological reasons, the description of which is out of scope for this paper. In light of the urgent need to reduce material waste and embodied carbon in the construction sector, this project explores the opportunities of redefining materials value chains through circular economy.

In particular, the reuse of structural elements is a promising strategy that is still scarcely studied. Contrary to recycling which requires energy to process material, e.g. to remelt steel, reuse extends the service life of components while limiting their physical transformation and changing their location and/or function. Reusable structural components may consequently have a longer service life than the systems to which they initially belong. Disassembled buildings become a mine for new constructions, and functional obsolescence is not a reason for waste production anymore.

1.3. Problem statement

The industry is currently lacking benchmarks to assess the beneficial impact of structural reuse. This paper therefore provides a first answer to the following question. How would the reuse of structural components be beneficial for reducing the environmental impact of office buildings and to what extents? In particular how impactful are design parameters that typically arise when considering reuse strategies, e.g. material transportation, cross-section oversizing, and selective deconstruction?

2. METHODOLOGY

The load bearing system of a steel frame five-story high office building is used as a case study. This building typology is commonly found in urban areas where land pressures and therefore demolition and transformation rates are high. The chosen building typology also fits within the available benchmarks (see section 2.1) for medium-rise steel office buildings. First, buildings of similar construction type, i.e. steel constructions with four to six stories, are selected from an industry-collected database. The embodied carbon of those buildings is analysed and defines the *benchmark*. This benchmark is then used to relate the case study to the existing practice. Second, the design of the case study is analysed and serves as the *baseline* of minimally required material quantities and embodied carbon related to its conventional construction. Third, embodied savings due to the reuse of steel structural components in the studied design are assessed. For various assumptions of cross-section oversizing, the savings are parametrically studied as a function of the impact related to selective deconstruction and transportation.

In total three scenarios are compared:

- *Benchmark* of existing buildings: the lower bound of the industry-collected office buildings;
- *Baseline* for a conventional office building: the new construction of a typical steel-framed office;
- *Reuse* design cases: parametric analyses of buildings reusing steel components from other, obsolete buildings.

This original methodology can be used to explore and compare more complex reuse scenarios or other case studies.

2.1. Benchmark of existing buildings

Benchmarking embodied carbon in structural systems of buildings has been historically challenging due to uncertainty and unavailability of data and due to the difficult comparability of buildings as complex entities [14]. Leading structural engineering firms have developed in-house databases to start benchmarking their own projects [15-17]. The Waste & Resources Action Programme (WRAP) initiated the collection of whole building life cycle assessment (LCA) results from industry, but only the end results of embodied carbon calculations were collected, leading to a lack of transparency [18]. In comparison, the *database of embodied Quantity outputs* (deQo, available at http://deqo.mit.edu) collects both embodied carbon coefficients (ECCs) and structural material quantities (SMQs) in recent constructions, which offers a greater degree of transparency to the users [18]. The process starts by extracting mass and volume of used materials from the bill of quantities or from building information models (BIM), shared by global structural design firms [14,19]. The Carbon Leadership Forum used the deQo data and other industry-collected databases and case studies to create the first benchmarks for embodied carbon in buildings [20-22].

The ECCs (expressed in kg_{CO2e}/kg) of the considered materials are then used to calculate the total embodied carbon of existing buildings, as shown in the following equation:

$$\text{Embodied Carbon}_{\text{building}} = \sum_{m=1}^{M} \sum_{l=1}^{L} SMQ_i \times ECC_i$$

where:

- m is a particular material or component in the building m = 1, 2, 3,…, M;
- l is the number of replacements within the lifespan of the building for each material l = 1, 2, 3,…, L;
- SMQ are Structural Material Quantities (kg);
- ECC are the corresponding Embodied Carbon Coefficients (kg_{CO2e}/kg)

Results from this data collection are evaluated and presented in boxplots. Figure 1 summarizes structural material quantities for all stored buildings with four to six stories and with steel as the main structural material. The SMQs are normalized by gross floor area. The diagram is divided into buildings with small gross floor area (up to 10’000 m^2) and big gross floor area (more than 10’000 m^2). The thick line inside the grey box of the boxplot reports the median value, whereas the boundary of the box indicates the inner quartiles.

Whiskers represent the minimum and maximum values.

Figure 2 similarly indicates the corresponding embodied carbon, normalized per gross floor area. What is considered in the material quantities and embodied carbon results shown in Figures 1 and 2 are the impacts related to the manufacturing and construction of the structural steel system, but also to slabs, connections, load-bearing walls included in the basement, a base plate, and foundations.

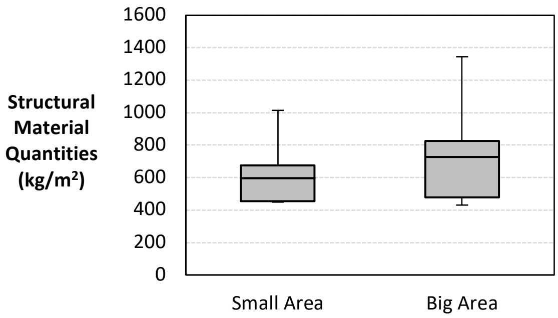

Figure 1: Structural material quantities of 23 existing steel buildings with four to six stories.

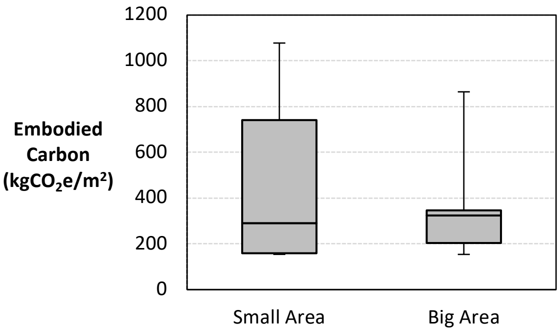

Figure 2: Embodied carbon of 23 existing steel structures with four to six stories.

To be comparable with the case study building introduced in the next sub-section, this subset of all deQo projects results from a query of similar structural systems, materials, and number of floors. From the hundreds of buildings in deQo, 23 entries currently correspond to the criteria aligned with these constraints.

2.2. Baseline building

To evaluate the environmental benefits of reusing structural components, the main structure of a baseline building is designed as a case study. The building is composed of a steel frame with steel columns and a grid of primary and secondary steel beams supporting prefabricated concrete slab elements. The conventional construction of this structural system is compared parametrically with scenarios where steel elements are reused from one or more dismantled buildings (see next subsection). The baseline building has a width of 32 m, a length of 60 m and a height of 17.5 m. The building has five stories, a story height of 3.50 m, ten bays in the length direction with a column spacing of 6.00 m, and four bays in the width direction with a column spacing of 8.00 m. A schematic view of the structural skeleton is shown on Figure 3.

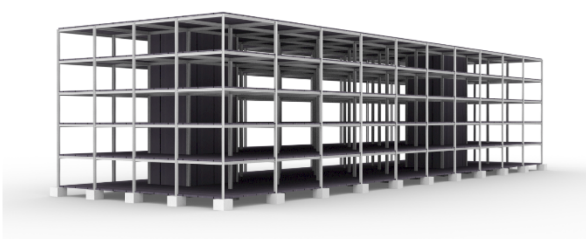

Figure 3: Schematic view of the case study structural system.

Dead load of the slab elements as well as a superimposed dead load of 2.0 kN/m^2 and a (conservative) life load of 5.0 kN/m^2 are considered. These assumptions are used to size the baseline structure from standard I-sections at ultimate limit state including standard safety factors. The general strategy for sizing is to utilize cross section capacities in the best way possible.

A life cycle assessment is performed to quantify the corresponding embodied carbon of the main structural elements. For the purpose of this study, an ECC for the production of new steel, including a typical recycled content, equal to 1.10 kg$_{CO2e}$/kg and an ECC of reinforced concrete equal to 0.15 kg$_{CO2e}$/kg are used. These values are averages derived from the Inventory of Carbon and Energy [23], GaBi [24], Athena [25], and EcoInvent [26], evaluated in [9]. In addition to production, impacts related to the transport of elements over 110 km to the building site are considered. The transport emissions of 0.36 kg$_{CO2e}$/(t·km) are obtained from [27] for typical road freights. The overall embodied carbon for a conventional construction of the baseline building (including the new production of steel elements) is 140 kg$_{CO2e}$/m^2 of which 39 kg$_{CO2e}$/m^2 are due to the steel elements, while 72 kg$_{CO2e}$/m^2 are caused by the slabs and base plate. The embodied carbon of the foundations, here assumed as 22.5 kg$_{CO2e}$/m^2, varies however greatly in practice depending on soil properties [28].

2.3. Reuse design cases

On the one hand, reuse avoids sourcing raw materials and requires little energy for reprocessing. On the other hand, reuse requires energy during the selective deconstruction of obsolete buildings as well as for transport, refurbishment and storage. In the studies of this paper, we only consider the reuse of load-bearing components.

To design a structure based on an available stock of reclaimed elements means that a-priori given geometric and mechanical properties of components might lead to a non-optimal capacity utilization of available elements that counteracts the potential savings through reuse [29-30]. Reused structural elements are ultimately oversized. Few quantifications of finally achieved benefits exist. Through a parametric case study, this research evaluates how much embodied carbon can be saved through the reuse of structural elements compared to a conventional construction.

2.4. Embodied carbon comparison

The embodied carbon of the conventional baseline structure is compared to the case where the same structure is made from reused steel elements. A parametric study analyses the sensitivity of environmental savings through reuse for two key parameters: selective deconstruction and transport related carbon emissions.

The total building material quantities of the case study building include the steel frame, the reinforced concrete slab elements, a base plate, elevation cores and foundations. The material quantities and embodied carbon associated with all non-steel elements are kept constant in the parametric study and are equal for both conventional baseline and reuse scenarios. The parametric study only focuses on the reuse of the structural steel elements. The quantities of all concrete elements are here included in order to allow a comparison of the baseline and reuse design cases to the buildings extracted from the deQo database. Connections, bracing systems, and secondary structure were not considered in this preliminary design, such that the resulting material quantities and embodied carbon will be on the lower bound of the case studies reported in deQo.

Figure 4 summarizes the steps considered for the LCA of the different reuse scenarios. It is assumed that the steel elements are reclaimed from obsolete buildings through selective deconstruction. This process includes the opening of connections as well as the hoisting of elements with a crane. A corresponding impact of 0.267 kg_{CO2e}/kg is reported in [29], which is based on a review of data provided by Athena in [30]. In the parametric study, this value is varied between 0.0 kg_{CO2e}/kg and 1.0 kg_{CO2e}/kg to account for the uncertainty of this data.

The transport distances are the second parameter analysed in the parametric study. Transport distances between 0 and 500 km from the deconstruction site over the fabrication site to the building site are considered.

The last parameter that is analysed is the cross-section oversizing of the structural steel elements. Indeed, when structural elements from an obsolete building are reused in a new configuration, not all elements can be used at a utilization level as high as in the original configuration. Among other reasons, this is due to the unavailability of desired cross sections [29]. It is therefore assumed that material quantities in reuse scenarios are 'oversized' compared to the conventional case where cross sections are selected with optimal size. The extra steel mass is parametrically varied between additional 0 to 50 % of the material quantities used in the baseline building.

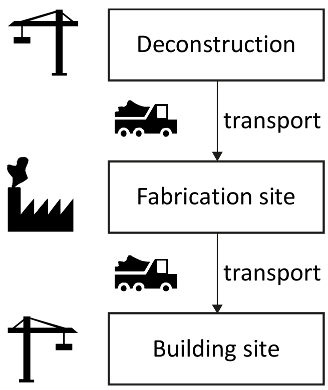

Figure 4: Diagram representing the impacts of reuse

3. RESULTS

3.1. Influence of transport

Figure 5 illustrates the influence of transportation distances on the embodied carbon of the reuse design cases. The considered oversizing of steel element mass is expressed in 10 % steps by the corresponding grey lines. In addition, Figure 5 shows the lower bound benchmark, i.e. the first quartile (Q1) of collected low area steel buildings (section 3) as well as the embodied carbon of the conventional baseline building. It is visible that even with 50 % oversized steel element sections and a transport distance of 500 km, the embodied carbon of the reuse design case does not exceed that of the conventional load bearing system. These results indicate that longer transport distances are acceptable in order to facilitate the supply of reclaimed steel elements. Only when considering transport distances over 2000 km and an oversize ratio of 25 % the embodied carbon of the reuse case would exceed that of the baseline case.

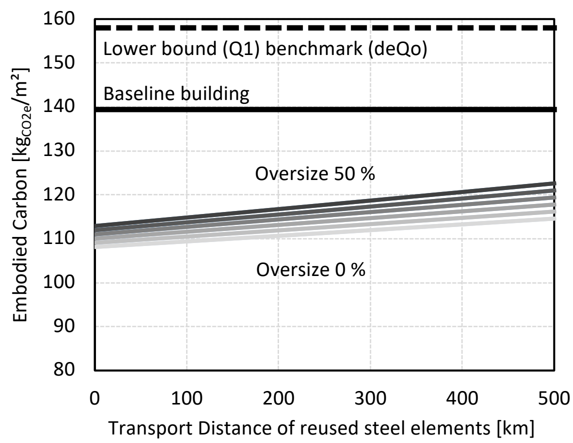

Figure 5: Embodied carbon of benchmark lower bound, baseline and reuse design cases for varying transport distances and oversize percentages.

3.2. Influence of selective deconstruction

Figure 6 shows the influence of selective deconstruction related carbon emissions on the total embodied carbon of the load bearing system made from reused elements. Again, grey lines indicate the considered percentage of element oversizing. The reference ECC of 0.267 kg_{CO2e}/kg for selective deconstruction obtained from [29] is also indicated. The results show that embodied carbon of reuse design cases only exceed the embodied carbon of the baseline building when elements are oversized and impacts of the selective deconstruction are unexpectedly high. As introduced before, the reference impact of new steel production is 1.1 kg_{CO2e}/kg.

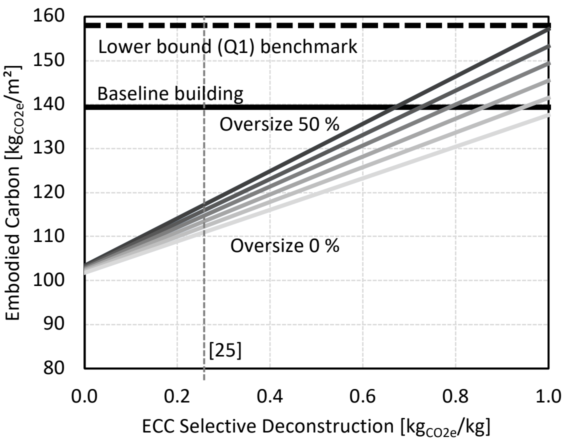

Figure 6: Embodied carbon of benchmarked lower bound, baseline and reuse design cases for varying selective deconstruction values and oversize percentages.

In general, the obtained results show that when oversizing and emissions spent for transport and selective deconstruction are low, the benefits of structural reuse are significant. The potential savings in greenhouse gas emissions through reuse relatively to the baseline conventional building can be up to 20 % when considering the reference impacts for selective deconstruction, a transport distance of 300 km and only 25 % oversizing.

4. DISCUSSION AND CONCLUSION

This paper presents the study of a structural system for an office building realised with new steel elements and with reused structural elements. The embodied impact of the building is computed parametrically and compared to data collected industry-wide.

Results show that for this case study embodied carbon savings of 20 % can be obtained by designing with reused structural elements. It should be noted that the parametric study is only applied to the steel structural skeleton. The foundation, core and slabs are kept at a constant amount of materials. It is assumed that the same concrete quality was used in all concrete elements and the same steel quality in all steel elements for simplicity of the modelling. In addition, impacts of new connections, bracing system and secondary structure are not taken into account. Further research should give separate coefficients for slabs, foundations, cores, connections, and bracing elements. However, as these values are kept constant in this case study, they do not influence the relative comparison of results.

The embodied carbon savings would be even higher if the prefabricated concrete slabs could be equally reused. Indeed, the slabs contributed about half of the total embodied carbon in the baseline building. This confirms previous findings [32] that slabs are the structural elements with the highest environmental impacts in typical building structures.

Results show that reuse remains beneficial even when transport distances, selective deconstruction related impacts, and oversizing are relatively high. Only when selective deconstruction and oversizing are both much higher than expected, the impacts exceed those of a conventional new construction. Impacts due to selective deconstruction are currently computed as ratios of structural mass, it therefore depends on the oversizing. In practice, however, it may be assumed that selective deconstruction is much more related to the complexity of the disassembly process than the weight of the system. Future studies should therefore include ECCs for selective deconstruction that are not directly dependent on mass.

In future research, different scenarios will also include the impacts calculated over multiple life spans, with the functional unit being one service life. Such scenarios would account for material degradation more precisely. The parametric study should also be extended to concrete elements and should address serviceability constraints. Further, an optimization of the utilization of available stock elements would allow the reduction of oversizing and allow an informed design processes. In this paper, refurbishment, storage, new connections, and remaining structural capacity are neglected. Future work can expand on including the impacts related to these aspects.

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